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Investigation of Imaging and Flight Guidance Concepts for Rotorcraft Zero Visibility Approach and Landing

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FOREWORD

This effort was performed under NASA Contract Number NAS2-11364 from the NASA-Ames Research Center. Mr. George R. Clary of NASA-Ames was the technical monitor for this project. Mr. George E. Tucker, NASA-Ames pilot staff, served as a pilot test subject in the formal simulated flight phase. Mr. Clary also participated as observer during the simulated flight phase.

Mr. William L. McKeown, at Bell Helicopter Textron Incorporated, was the project engineer and technical support was provided by Mr. Hubert Upton, Mr. Robert Gardner, Mr. Peter Klein, and Mr. Richard Philbrick.

1. INTRODUCTION

During adverse weather conditions, helicopters have more severe flight restrictions than fixed-wing aircraft. The capability of operating a helicopter in adverse conditions is reduced because of the increased chances that obstacles, low ceilings, and errors in controlling the flight path will jeopardize safety. Highly controlled conditions at airports, including sophisticated ground-based equipment, have made it possible for airplanes to land with very low ceilings in piloted flight, or with zero visibility in automated flight. For the helicopter to operate in these conditions, where ground guidance systems are minimal or nonexistent, self-contained sensing systems are an obvious requirement.

Many studies have been done to investigate the feasibility of zero-visibility helicopter operation using various combinations of sensors, controls, and cockpit displays. The general conclusion has been that imaging sensors are needed to provide adequate safety. The images must contain sufficient information to allow the pilot to control the helicopter (rotorcraft) and to avoid hazards. The information must be clearly displayed and easy to interpret. This generally means that the information should be presented in a form equal to, or closely analogous to, the real-world visual situation. Other system requirements include accuracy, reliability, ease of training, and weather penetration capability.

Some candidate imaging sensors include forward looking infrared radar (FLIR), radar, and laser systems. These systems and others may be needed, either separately or in combinations, to allow zero-visibility helicopter operation. However, these systems will probably fall short of emulating a real-world view from the cockpit, especially from the field-of-view standpoint. Some type of additional assistance will be needed in the form of symbolic displays and added stabilization to reduce pilot workload.

The objective of this project was for BHTI, in cooperation with NASA personnel, to define a program and perform a fixed base simulation to examine the ability of helicopter pilots to use an imaging display to accomplish landing approaches, hover, and touchdown. The incorporation of symbology on the imaging display was examined to determine improvement in pilot performance as a function of added symbology. This symbology was selected as a function of the use of sensors planned for the aircraft mission equipment package studied under this contract. The degree of artificial stability and control needed to allow mission performance was also examined. The results of this project will be used to further establish a baseline program for a future moving-base simulation program at NASA.

This project was divided into three phases: Literature Review, Test Configuration Development, and a Formal Test phase. The literature review was aimed to eliminate any effort that would duplicate the work of earlier investigations. The literature review also served to suggest ideas for new concepts or combinations not previously demonstrated. Section 3 of this report presents the literature findings and the conclusions leading to the development of a variety of simulation test elements.

The development phase was used to generate a simulation environment and a set of test configurations consistent with the program objectives. Sections 4 and 5 of this report present a description of the simulation equipment and the development of the symbology and control system. The experimental procedures and experiment design are also discussed in Section 5. This section is supported by Appendix A, which includes the experimental program test plan. Appendix B presents some details of the control system and performance data.

Section 6 presents the methodology used in gathering and analyzing the data, while Section 7 summarizes the findings and results of the formal test program. Section 8 describes recommendations for the follow-on program to take place in a NASA moving-base simulation facility.

2. SUMMARY

The purpose of this project was a preliminary study [illegible]e use of an imaging display in a rotorcraft zero-visibility approach and landing system. The program included a literature review, experimental system design, and a series of tests in a fixed-base simulated flight situation. The results of this project are to be incorporated into a future simulation effort run in a NASA moving-base simulator. The driving factors for this effort are:

1. To extend rotorcraft operational capability into instrument meteorological condition (IMC) flight for areas normally flown by the same craft in VFR conditions.

2. To provide this capability at a reasonable cost, safely, while providing the pilot with information he can use in a "natural" way.

The imaging sensor/display concept provides the self-contained requirement as well as a natural set of cues for the pilot. The effort concentrated on a high-resolution rotor-mounted radar as the imaging sensor. A graphics display generator was programmed to generate an expanding-scale pictorial display which represented the radar image. The same generator was programmed to produce symbolic displays superimposed on the pictorial display. Based on the literature review and preliminary flights in the simulator, an experimental system was developed for use in a formal test phase, where several test pilot subjects participated in a simulated flight evaluation. A criterion during development was to avoid designs using command indications to the pilot. The control system was designed to provide attitude stability and to follow pilot commands on a rate or attitude basis.

Only a few basic combinations of the display and control system were found to be adequate to allow deceleration, hover, and touchdown on a 100 ft (30.5m) square pad. The results of the formal test phase showed a small spread in the subjective and objective ratings of the various combinations. This indicates that the development phase may have reduced the experimental

design variations more than necessary. The criteria may have done so, also. The criteria of completing the mission without command information, navigational automation, direct aircraft velocity control, or a wide field-of-view presentation all together called for a minimum set which was somewhat elaborate. This tended to limit other configurations to minor variations.

The expanding-scale pictorial display provided the cues needed to control the aircraft position in three dimensions. The narrow field-of-view provided by the display caused the image scaling to be distorted at low altitudes, especially below 200 ft (61 m). The result seems to indicate a problem in determining height from the image alone. A "zooming" sensation below 200 ft (61 m) was experienced by the test pilot subjects and required more attention to the symbolic altitude scale to determine actual descent conditions.

Horizontal position was more precisely controlled when velocity and acceleration were explicitly displayed. The Human Factors Engineeering pilot noted that touchdown velocities of approximately 4 feet per second (1/2 m/sec) were achievable without velocity displays, while 1.5 feet per second (0.5 m/sec) was a typical value with the displays. This indicates that improvements in the pictorial display might eliminate the need for explicit display (and sensing) of ground velocity.

The addition of more display elements tended to create a "clutter" effect and ambiguous interpretation perhaps resulting from the use of a monochrome display and the need for simple, graphic, radar imagery representations. A greater contrast might improve the display to the extent that explicit velocity data would not be necessary.

The results of this effort indicate that imaging displays can be potentially very important to accomplishing the mission. The training time required indicates that imaging displays provide natural, easily interpreted information. Although hovering and landing precision during zero visibility was not

adequate during this project, landing and hovering precision should be addressed in future, more comprehensive simulation efforts. It is recommended that a scaling algorithm which produces a realistic sensation of height on a reduced field-of-view display be developed.

3. LITERATURE SEARCH

There have been many simulation and flight programs involving helicopters in IFR flight. Only two programs have studied approaches and landings under completely hooded conditions (simulated zero-zero) (References 1 and 2). References 3 and 4 report on landing experiments with pictorial type displays. The literature is particularly voluminous where a breakout ceiling existed and the final approach was ended at breakout; landing was not part of the programs discussed in References 5 and 6.

Many principles have been established by these programs, showing trends and interrelationships between many configurations of sensors, controls, and displays. These combinations have included a wide range of sophistication in sensing, control and/or displays, ranging from the situation where the pilot is a simple monitor or servo command follower, to systems where better displays allow him to be a command generator.

Few programs have addressed the entire problem of helicopter zero visibility, decelerating approach, hover, and landing at remote sites, away from normal air terminals. In this project, it is assumed that area and point-to-point navigation problems have already been resolved.

The emphasis in this literature search was to review earlier work in the use of imaging systems and sensor/display complements as applied to remote landing sites in particular. This intent coincides with the main thrust of the present project, which is to use imaging displays to offset the need for elaborate displays, controls, sensors, and ground-based guidance equipment, and let the pilot use natural cues from the displays.

During the literature search, it became apparent that control-law and display tradeoffs are closely related, and that there are many systems that use only symbolic display information. In most systems, much of the symbolic information to be displayed is concentrated in one area to reduce scanning for information. This concentrated information only creates confused clutter in

the display. Real-world information is in fact more cluttered than the symbolic display, but the real-world information is easily interpreted. Imaging displays which present a real-world like picture should therefore be valuable in resolving the symbolic display problem.

Much work in using contact-analog displays (References 20 and 21), FLIRs (Reference 22), and computer-generated imagery (CGI) has been expended toward proving this point. In this project, we are directing our effort toward self-contained systems having imaging sensors, as well as imaging displays, so we can operate in unprepared areas.

System concepts for helicopter IFR to remote areas were investigated in Reference 7. Emphasis was placed on sensors to provide pictorial images. These sensors use a wide part of the electromagnetic spectrum; radars use microwave frequencies from 5 to 100 GHz; FLIRs use the infrared band; and television uses the visible spectrum. Television images, and to a great extent FLIR images, have an advantage in that these images look real, similar to perspective views of a scene (i.e., landing sites, obstacles, and other objects).

Reference 3 reports on low light level television experiments where approaches and hover were accomplished using the pictorial displays. There were problems with the narrow fields of view, but it was proven again that pictorial displays are of great value in providing cues that pilots normally extract from their external view. It has also been shown (References 8 and 9) that varying degrees of success can be achieved with television and FLIR displays augmented with symbolic information. In Reference 8, hover was achieved, but with great difficulty. In Reference 9, breakout at 46 m (150 ft) was assumed.

Unfortunately, television FLIR and radars that operate in the millimeter wavelengths are severely attenuated by rain and fog in the atmosphere (Referance 10). These sensors are not well suited for operation in heavy rain and fog conditions.

Reference 6 reports on the evaluation of a helicopter rotor radar which used a rotor mounted antenna to achieve a very high resolution radar image. The results indicate that by using an elevation monopulse radar to measure glideslope and by marking the touchdown point on the high resolution map, excellent hooded approaches could be accomplished down to 46 m (150 ft). The range scale was reduced with altitude so that landing spot information seemed to expand in size on approach much like the real world does on a contact approach. The display was not in perspective, but this characteristic could be added.

It is a goal of this program to develop an imaging display and augment it with improved symbolic information which emphasizes actual situation information, avoids command information, and minimizes control system complexity.

In reviewing literature for pertinent information showing trends and principles, it is appropriate to make use of other literature searches. Reference 11 is a comprehensive survey of investigations into the control/display problems of instrument decelerating approach. This survey does not emphasize imaging displays, but some conclusions show trends that can be extrapolated into the imaging display area as follows:

a. A constant-attitude deceleration profile is preferred over constant deceleration.

b. A roundout or final constant altitude segment just prior to the hover point is strongly desired by the pilot.

c. For symbolic displays, at least, attitude command control systems allow the use of situation information alone to obtain precision hover.

d. While hovering, explicit display of horizontal translational velocities is required, even with a video image.

e. An attitude command system can eliminate the need for attitude display in the symbolic portion of the display.

f. A command velocity profile must include air- and ground-referenced phases to account for wind conditions.

In general, this survey (Reference 11) supports the idea that display and control tradeoffs are about one-for-one, that is, each level of integration added to the control system removes the need for one in the display.

The conclusion that one must explicitly display horizontal velocity indicates a shortcoming in the video display system. Inadequate resolution, field-of-view, or some other deficiency eliminates the normal real-world information needed by the pilot. There is a strong implication that a display would have to closely resemble the real world in all respects to eliminate this velocity display requirement. References 5 and 8 corroborate this conclusion.

Imaging Display Systems

An expanding-scale radar image is a novel addition to the display repertoire, and is designed to present radar imagery in a format resembling the external view familiar to a pilot on approach. An extensive evaluation of the HELMS high-resolution radar, which used an expanding-scale display, is reported in Reference 6. The flight tests proved that under-the-hood approaches could be made using the expanding-scale display and conventional flight instruments. The flight tests were performed in a UH-1 helicopter with no electronic controls. The breakout altitude was between 30.5 m (100 ft) and 61 m (200 ft), and forward velocity was not reduced below 31 m/s (60 kn) on instruments. One advantage of the radar sensor as compared to the FLIR and TV sensors is that range to objects is inherent in the forming of the radar image and can be displayed as discrete information.

The success of the HELMS approaches and the favorable pilot endorsement of the expanding-scale display makes the evaluation of this concept for transition, hover, and landing desirable. However, problems arise in continuing the expanding-scale display concept to hover. These problems are mainly associated with the fact that during transition and hover, it is desirable to display a wide area around the helicopter with associated peripheral cues. Unfortunately, the imagery, whether from a radar, FLIR, or television system, is usually displayed on a 13 cm (5-inch) to 25 cm (10-inch) diameter CRT in the instrument panel.

During the critical termination phase of the approach, the pilot normally uses cues from wide-angle peripheral vision, as well as cues from foveal vision. When shown on a CRT, even if the view is of a wide area, the image appears as a greatly magnified view in the pilot's foveal vision area only. Not only is the small size of the image a problem, but the image cannot be spatially registered with all of the external points it represents. As the helicopter rotates in pitch, particularly in transition, the view representing external objects does not provide a spatial match to actual positions. These visual inaccuracies present potential problems in interpreting helicopter attitude and translation using the expanding-scale display. The realism of such a display, with attendant pilot acceptance and good performance to 30.5 m (100 ft) breakout, is probably because early in the approach, pilot attention is concentrated on the landing area, which subtends a small angle at the ground end of the approach path. The expanding scale image is easily displayed in correct registry with the objects. The image expands slowly until the final approach segment. The primary question concerns how to render the imagery and symbology effective throughout transition, hover, and landing. Available literature provides little information:

a. The expanding-scale imaging display system has not yet been evaluated at slow speeds and hover.

b. There is little information on any type of imaging sensor and display at hover.

c. There have been only a few programs which have investigated helicopter flight on instruments at slow speeds and hover.

A program conducted by the U.S. Army and reported in Reference 1 used a ground microwave scanning-beam landing system as a sensor to guide a UH-1 helicopter along a decelerating approach to a hover over a spot. The helicopter was equipped with a four-axis autopilot system for the approach experiments. The flights were programmed by the electronic system, and the pilot was given commands via a four-cue flight director. In later flights, a coupler was used to make the approach, transition, and hover automatic.

A similar success was achieved in a NASA program reported in Reference 2. A CH-46 helicopter was guided by a ground-tracking radar to piloted and automatic approach and landings. For the piloted approach, the investigation included variations in flight-director control laws, glide-path angle, deceleration profile, and control response characteristics. An attitude-augmented/command control system was used for successful performance, along with a three-cue flight director, which was implemented with flight director control laws to direct the helicopter along the approach path and through deceleration to a hover. Pitch, roll, and power were commanded by the flight director.

Although the pilots could make successful approaches and decelerate to a hover by devoting full attention to centering the flight director, they objected to the high workload servo-like task. They did not have time to scan other displays for situation information. A display which better integrates situation and command information was suggested as the solution.

In both instrument landing projects, described in References 1 and 2, very elaborate ground-based radars were used. The programmed approach and deceleration was accomplished either by the pilot acting as a servo, via the flight director, or the system was fully automated.

The objective of the Imaging and Flight Guidance program is to accomplish instrument approaches to any helicopter landing site, including sites in remote areas, with a self-contained onboard system. This eliminates the possibility of having to follow ground guidance signals and suggests the possibility of using good situational information, sensed in real time with onboard sensors, for guidance control.

The HELMS (rotor blade radar) expanding-scale display, described in Reference 6, provides excellent situation information which was augmented with symbols by which the pilot could control progress along the approach path. The HELMS expanding scale display did not provide a directed approach, but was similar to a contact approach where the pilot continually observes the spatial situation and maneuvers the helicopter as necessary to approach and land. The question is: can the expanding-scale imaging display be augmented so the pilot can decelerate and hover?

Cues Derived from Imaging Display

From the expanding-scale radar image, a list of expected information (aside from obstacle detection and other benefits of the radar) might include the following:

a. Horizontal position

b. Horizontal velocity (derived by pilot)

c. Vertical height

d. Vertical velocity (derived by pilot)

e. Ground track

f. Pictorial view of landing site

g. Heading

The capability to derive adequate information for the hover task will depend on the radar resolution, display scaling, and target characteristics (contrast, reflectivity).

In particular, the derivative information available will depend on image textural properties. The horizontal position information will be displayed with adequate resolution to obviate any need for symbolic displays. The actual resolution may determine whether or not adequate velocity information can be derived strictly from the pilot's visual process.

Velocity Symbology

With a reduced display field of view, it is likely that the sensitivity and rate resolution will be either marginal or inadequate. Therefore, it was appropriate to include explicit horizontal velocity in symbolic form as an element of display symbology to be investigated in flight simulation.

In considering the form of symbol to be used, it was natural to draw on prior developments, in particular, a set of symbology for the AH-64 helicopter (Reference 12, Format IV). The set includes a line originating at the helicopter symbol (fixed on the display) and pointing as a vector in the ground velocity direction from the helicopter. The length of the line represents the magnitude of the ground velocity vector. Also included is a vector to indicate acceleration, represented by a small circle displaced from the tip of the velocity vector by the acceleration magnitude. The velocity and acceleration symbols are included in the photographs of the simulator displays shown in Figures 4-9a, 4-9b, and 4-9c of this report.

The vertical velocity is also likely to be difficult to discern from a small imagery display. Accordingly, it was appropriate to draw on the Reference 12 symbology for vertical rate information, especially for the high sensitivity required at the hover point.

Control Systems

Automatic flight control systems or stability augmentation systems are generally an integral part of helicopter IFR-qualified systems. For the hover and touchdown zero-visibility mission, automatic flight control and stability augmentation systems are always an important part of the overall system and reduce pilot workload to some extent. The degree of response and stability augmentation have been studied and traded against many types of displays, command indicators, and sensors. The zero-visibility IFR mission demands high reliability, and for this reason complex sensors and computational equipment should be avoided where possible.

In reviewing pertinent literature, it is notable that the low or zero ceiling IFR missions have required highly augmented command modes and stability for all systems except those using displays which emulate the real world and provide adequate texture, perspective, attitude, height, etc. (see References 3 and 4). Systems that use conventional instruments (pointers, etc.) without imaging systems, have required the most augmentation. In fact Hoh, et al., (Reference 13) suggest that a velocity command mode will be required, no matter what displays are used. This conclusion was obviously based on a particular conception of what "advanced" displays might amount to in the near future. The added sensor complement required to implement this mode would certainly add control system cost and impact both system reliability and fault tolerance. (If the offsetting display requirements add the same sensor needs, the same problem exists.) Again, it is hoped that visually derived information from imaging sensors can be applied to eliminate other sensor needs and keep the flying process more natural.

The problem of sensing hover position with low signal noise levels and adequate precision is far from trivial. The pilot's ability to "filter" the image for useful information is difficult to emulate. However, the landing spot location might be sensed from the image information. This capability would require a technique similar to the video-tracking scheme used in the Reference 14 program. First, the pilot would select a landing spot from the

image, while at a relatively high altitude and at some distance away. The pilot would then place a cursor over the spot to pin-point the video to be processed and initiate a "lock" command to the video tracker. The aircraft position could then be determined by processing the video and treating the output as beacon information.

Assuming the pictorial display is augmented by symbolic elements, provides sufficient cues, and the aircraft has an attitude-command and an attitude-hold system, then the pictorial display should suffice to make the hover and landing mission feasible. This assumption is given support by Reference 15, Corliss, et al., which indicates an attitude command system is good for the deceleration and hover phases (if not up-and-away flight). In fact, evidence exists that attitude need not be explicitly displayed at all, if an attitude-command mode is supplied. The absence of attitude information on the transition and hover formats of the AAH electronic displays (Reference 12) is noteworthy.

Results of the Literature Search

This literature search indicated a probable need to provide supplemental cue symbology to the pictorial information, including velocity displayed as explicit information. It also indicated an attitude-command control system mode to be a necessary part of the experimental repertoire, with lesser modes not likely to be successful. Some display formats could be drawn upon directly (Reference 12), but specialized display formats might be needed, depending on the detailed characteristics of the imaging display.

4. DEVELOPMENT OF EXPERIMENTAL SYSTEM

Display Development

A display symbology set was developed for use in preliminary simulated flight experiments of the zero visibility approach and landing task. The purpose of these experiments was to evaluate a large set of display elements and reduce the set to a practical size matrix for formal evaluation by a number of pilots. The preliminary simulator flights were made first by a human factors engineering pilot, and later by an experimental flight test pilot. Their experience was used to eliminate obviously deficient configurations and to provide input to the creation of new configurations or improvements to others.

A set of symbols was designed to provide visual cues to supplement those available from the simulated radar pictorial display. The display symbology was based on results of the literature search and the available simulation equipment. It was necessary that the pictorial and symbolic display elements be generated and displayed by the VECTOR GRAPHICS G-80 system. The G-80 software was written to obtain the maximum use of the system, with update rate being the most critical tradeoff against the complexity of the combined pictorial and symbolic elements to be displayed. As the development progressed, these tradeoffs were made continuously, in that the pictorial display, representing the radar image, was simplified as more complex symbolic elements were added. Because a primary goal of this program is to evaluate the usefulness of imagery, emphasis was placed on maintaining enough detail in the pictorial display to provide the cues to be expected (and needed) from the radar system.

Early in the simulated flight experiments, it became obvious that the final decelerating approach and hover phases are the most demanding flight modes. This conclusion is not surprising, in light of the evidence developed in many other programs; therefore, it was decided to concentrate the final decelerating approach, hover, and landing. It was also decided to begin this

phase with speed already reduced to a low value, appropriate to the zero-visibility IFR mission. The speed chosen was 21 m/s (40 knots) IAS. This speed is slow enough to cause poor handling qualities in most helicopters unless SCAS equipment is operating to assist the pilot artificially. This factor was borne out immediately in simulated flight experiments. The 21 m/s (40 kn) IAS and an operational SCAS were used as the initial approach speed for all experiments. This assumes an aircraft (rotorcraft) system architecture containing a highly reliable, redundant SCAS system. The Reference 11 survey points to this need as being fundamental to system success.

With regard to system architecture, an important criterion in developing the experimental symbology was to maintain a realistic relationship between the sensors and system equipment needed to drive a given display element. Each new symbol was evaluated for compatibility with a sensor or sensor set within a potentially viable system architecture. The relationship to system architecture (sensor requirements) is described within the discussion of each display element in the following paragraphs.

Pictorial Displays. The goal for developing the pictorial display was to generate pictorial details which would provide the same cues as are to be expected from a high-resolution imaging radar which has an approximate azimuth and minimum range resolution of about 13 m (40 ft). This would allow the system to display the outline of a 30.5 m x 30.5 m (100 x 100 ft) landing pad. Table 4-1 lists the cues to be expected and corresponding pictorial elements which might provide adequate cues.

Items 1, 2, and 5 in Table 4-1 call for a reference of some sort showing the location of the helicopter. The reference must be symbolic, but the location on the display provides the present location cue and determines where the pictorial displays are located and rotated. The other needed elements are recognizable objects. A display which contained outlines of objects, easily drawn with simple vectors, was developed to provide a simulation of a high resolution radar plan position indicator (PPI) image. Figure 4-1a illustrates the largest area view developed. The details include some roads, buildings, a

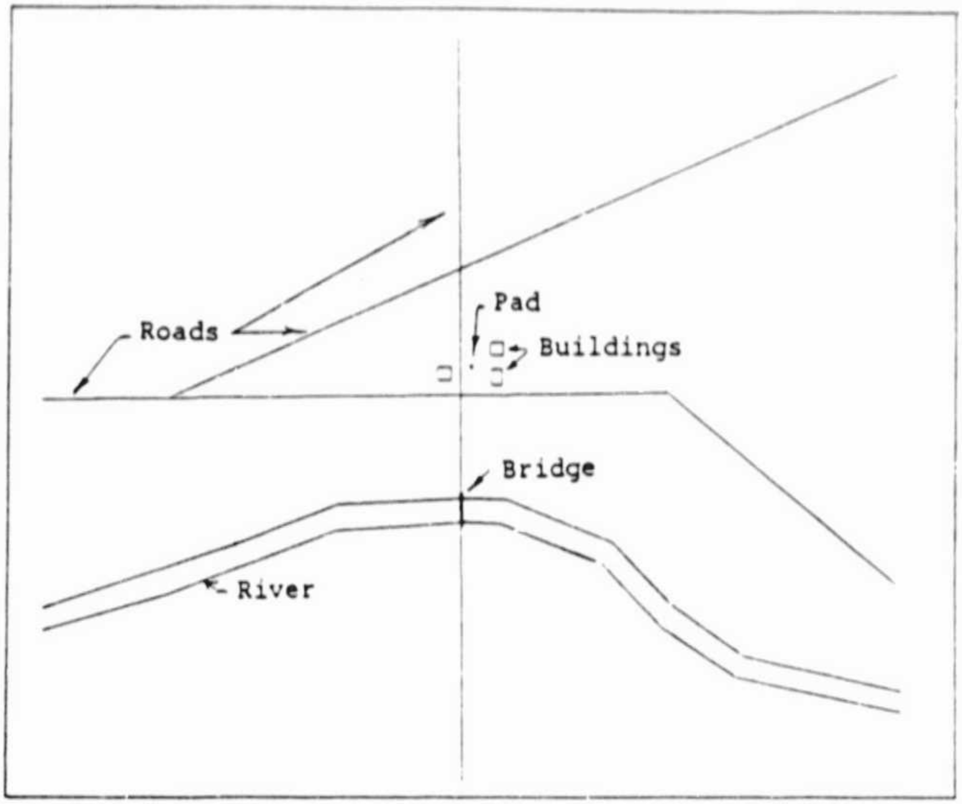

Figure 4-1a. Large area pictorial display.

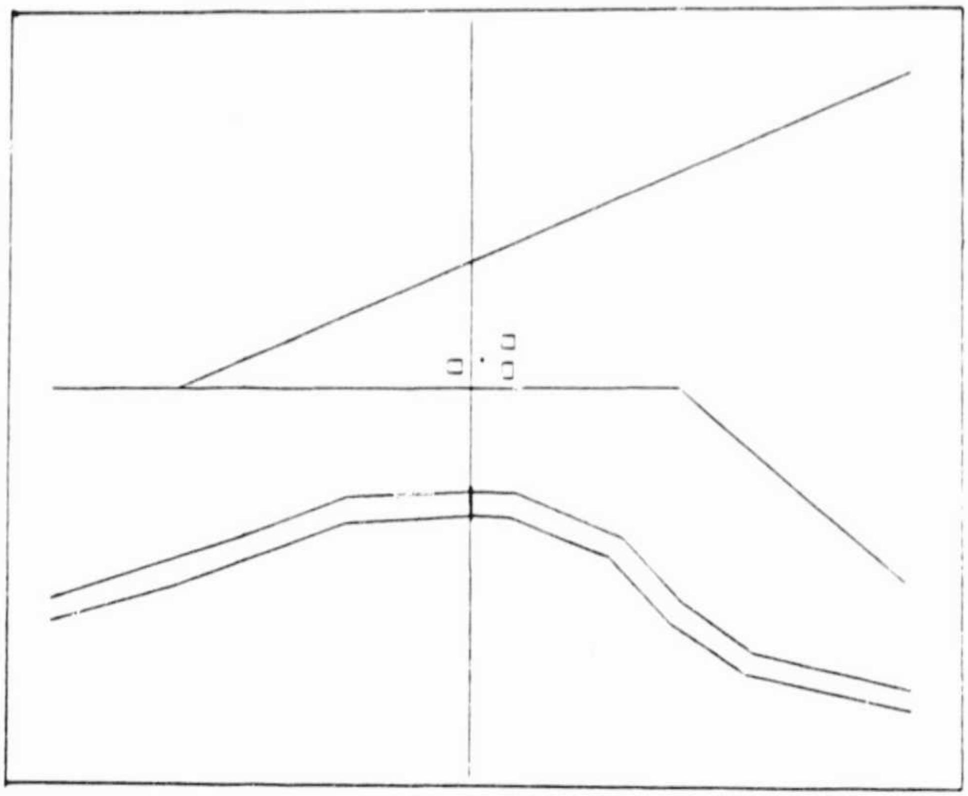

Figure 4-1b. Large area pictorial display.

river with a bridge and the landing spot. Figure 4-1b illustrates the same scene without the designations, shown for clarity. These details were considered adequate to provide the cues noted in Table 4-1. At the same time, the amount of detail was minimized to help maintain a reasonable update rate and to allow a test subject to quickly learn the meaning of each pictorial element.

Most of the illustrations in this section are derived from reproductions of the graphics generator output as it appears in a plotter output. Some of the lines have been made heavier to illustrate contrast in the final CRT image. Near the end of this section, a set of photos from the CRT screen are reproduced to illustrate the contrast appearing on the cockpit CRT. In television and FLIR pictorial displays that have perspective cues, a landing site expands on the display during an approach just as a real world scene does. However, a radar map display has size determined by display scale. In order to provide size change cues to the pilot, the HELMS system (Reference 6) expands with decending altitude, thus showing a change in object size as the object is approached on the glideslope. Tests proved that this system provided an excellent means of simulating the natural expansion seen in contact approaches.

TABLE 4-1. CUES FROM IMAGE DISPLAY

Parameter	Required Pictorial Cue
1. Present location	Helicopter symbol location plus pictorial landing pad
2. Range and range rate	Objects of distinguishable size and character, e.g., roads, buildings
3. Height above terrain	Size of recognizable objects
4. Heading	Orientation of scene
5. Ground track	Direction of motion of helicopter symbol with respect to objects or terrain

Expanding Scale. Because of the success in using the expanding scale (Reference 6), it was decided to use the expanding scale concept in the simulated display. Additional details were added to enhance the pictorial display as the picture expands, simulating a real situation where smaller details become noticeable as the landing site is approached. Accordingly, details were developed and added to the pictorial display at certain steps of expansion. Figures 4-2a, b, and c illustrate the addition of details in the area of the landing pad and the surrounding buildings. No details were added in areas farther away because they would not be encountered at low altitude under normal approach conditions. The first addition (shown in Figure 4-2a) consists of adding width to the roads and parking lots adjacent to the buildings. Next, (Figure 4-2b) texture is added to the landing pad along with topographical texture in the surrounding area, followed by the addition of texture to the pad (Figure 4-2c).

Relation to Image Sensing. The pictorial display elements are representative of those which could be obtained using a high-resolution imaging radar, such as the rotor-mounted radar discussed in Reference 6. The scanning method is assumed to be the normal PPI radial scan with the display scale (and image size) controlled by altitude. The altitude sensing is assumed to be from one of two primary sources, depending on the landing area. In generally flat terrain, altitude can be measured using a radar altimeter. On elevated structures or pinnacle sites, a beacon is used to positively mark the landing spot. Altitude can then be derived from the radar range and elevation angle to the beacon.

Another feasible arrangement would be to use radar-reflective markers on, and/or around the landing pad, along with a video tracking system scheme such as used in Reference 16. The tracking scheme would provide beacon-type information in two dimensions. Radar altitude could be used for the third dimension or perhaps multiple radar reflectors could be used set in a known pattern using known separations.

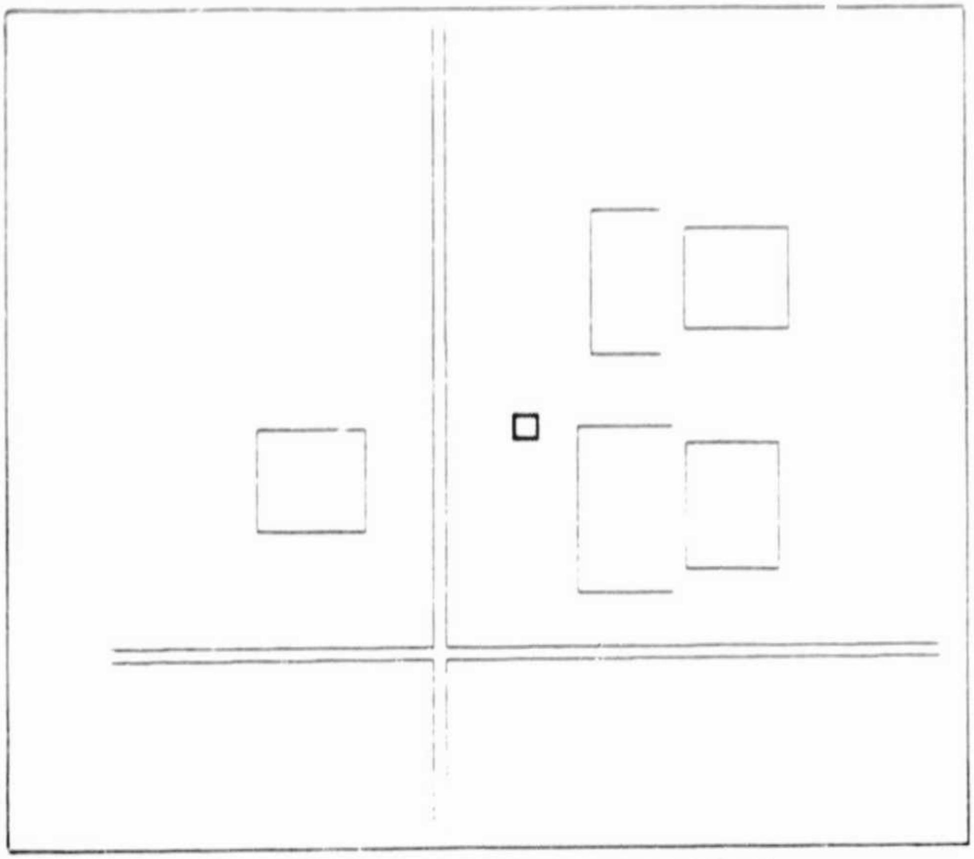

Figure 4-2a. Expanding pictorial view.

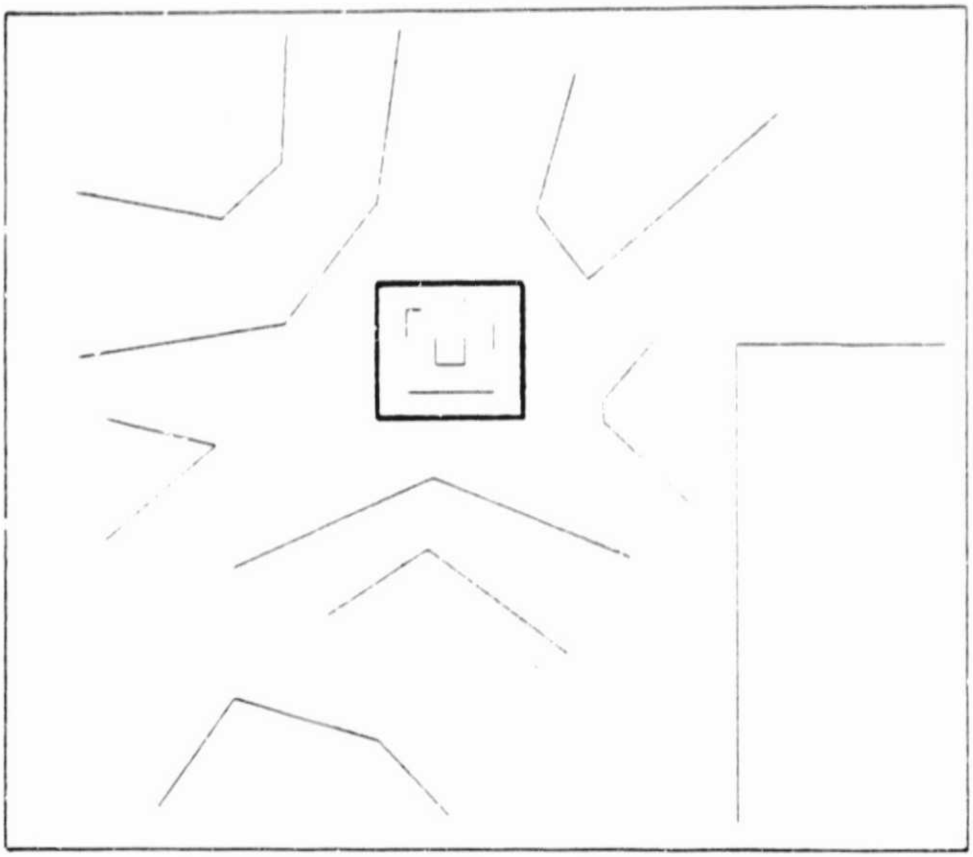

Figure 4-2b. Expanding pictorial view.

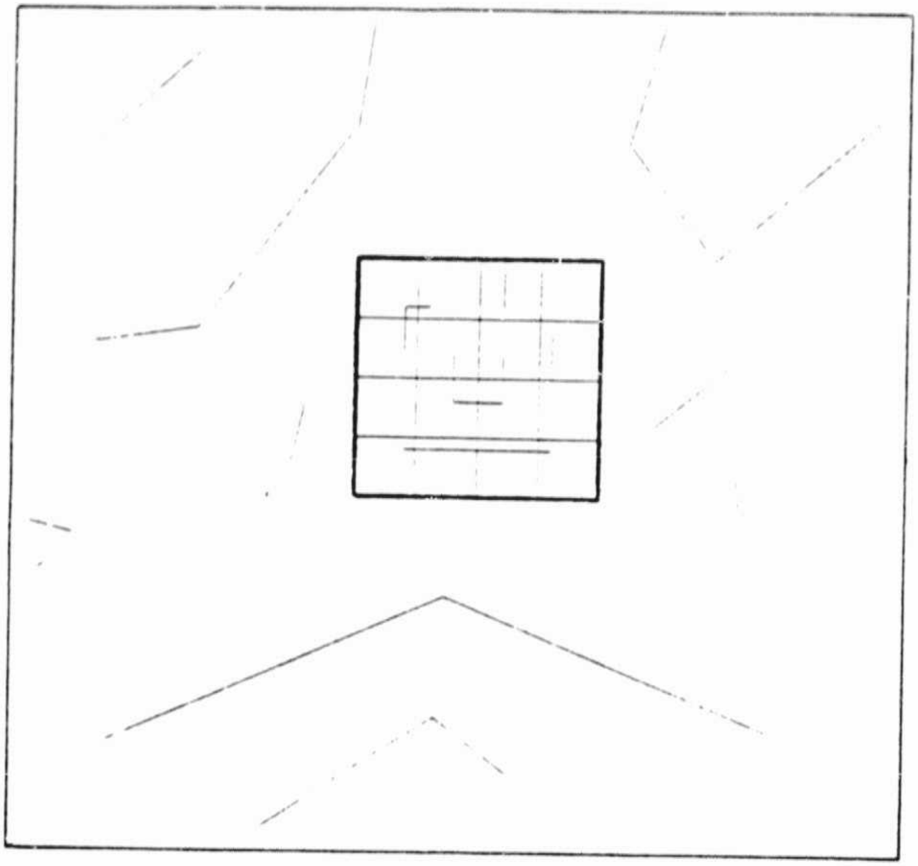

Figure 4-2c. Expanding pictorial view.

Simulated Flights

Simulated flights were made using the pictorial display, with symbolic displays (to be discussed later) providing basic information, such as airspeed, altitude, and vertical speed. Attitude information was available only from the attitude direction indicator (ADI). These preliminary flights were made with a rate-command control system having short-term attitude hold. It was possible to control the aircraft down to approximately 15 m/s (30 knots) IAS, at which point the workload was extreme and loss of control would occur on attempting to hover.

It became obvious that visual scan time is at a premium, so a symbolic attitude display was designed to be applied to the CRT display, superimposed on the pictorial information. Here difficulty was encountered with conflicting cues between those provided by the symbolic display elements and the pictorial elements. The superposition of attitude on the pictorial display caused confusion between roll vs yaw motions and pitch vs forward translation. Figure 4-3 illustrates the attitude display, which was superimposed on the pictorial displays. This display consisted of a rectangle, wing reference, and horizon line. In analyzing the problem, it was theorized that the conflict would be wholly or partially resolved when a more realistic pictorial display is used - especially one appearing less symbolic. Another theory was that color separation would help considerably. In any event, the decision was made that an attitude-hold, attitude-command system might make completion of the mission possible. Accordingly, this feature was incorporated in the control system for subsequent flights.

Another observed phenomenon was a consistent problem with pedal reversals experienced by both human factors and project test pilots. Analysis of this problem indicated an important relationship between the location of the helicopter on the CRT screen and the perception of being inside, looking out, or outside, looking down on a helicopter. The pictorial radar display is an inside/out display configuration; there was obvious confusion in how it was being interpreted.

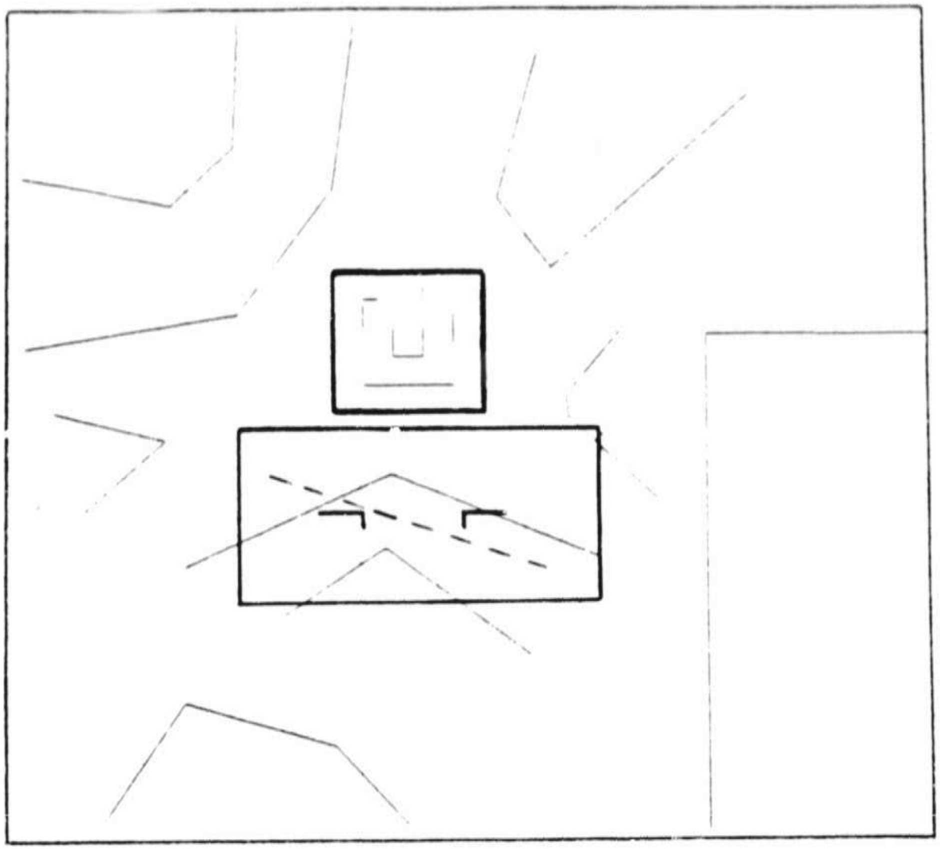

Figure 4-3. Attitude display.

For these early tests, the helicopter symbol was located at the center of the CRT. As the aircraft yawed, the lower 50% of the pictorial image moved opposite to what one can normally see in the real world. This conveyed a strong cue of outside-in. To obtain correlation between theory and actual experience, some motion picture film of radar images was viewed. The film was taken during a flight test program for a radar having a rotor blade-mounted antenna providing a high-resolution image (Reference 6). This radar had a sector display mode which placed the aircraft at the bottom of the screen and displayed only a forward sector of the radar video. The other mode placed the aircraft at center and showed all 360° of the video. When viewing one type of image immediately after the other, it was strikingly evident that a reversal takes place when the helicopter symbol is in the center of the display, the display is mistaken for an outside-in display instead of an inside-out display as intended.

It was necessary to eliminate this problem, without introducing new ones. Moving the helicopter symbol location to the bottom of the CRT screen, as it was in the sector scene version of the rotor radar, seemed very undesirable for the hover portion of flight. This would eliminate half of the landing pad from view as the helicopter hovers over the center of the pad. It also seemed undesirable to change the location of the helicopter symbol on the CRT screen, either smoothly or suddenly (with a mode change). Accordingly, it was decided to try a compromise arrangement where the aircraft symbol was moved to a fixed point toward the bottom of the screen. This placement caused the major area of the display to move in the direction of the forward portion, for yaw motions. The display configuration was changed to place the helicopter symbol one-fourth way up from the bottom of the screen. Simulated flights were then made by human factors and project pilots. The result was very positive; there were no more pedal reversals attributable to misinterpreting the display.

Fixed-scale changes and symbology changes for different modes of flight or segments of the approach were deemed necessary or useful. Accordingly, the

approach was divided into five phases - cruise, entry, approach, transition, and hover. It was felt the cruise mode would naturally call for a large area to be displayed. This mode was given a fixed-scale change and pushbutton selectability from a switch located on the CRT bezel. The other modes were provided to control changes in the symbology as the flight progressed. The other mode changes were initially made to be automatic, based on range and altitude parameters. Early flights indicated no problem with the manually selected change from the CRUISE mode to the ENTRY mode. However, accommodation to automatic mode changes was found to be very difficult. The sudden changes were quite disturbing and were not always expected, if the parameter causing the change was not carefully monitored. It was theorized that part of the problem had to do with the pictorial display consisting of elements that were symbolic in appearance. In the dynamic situation there was confusion between the picture elements and the symbols. Sudden changes tended to require renewed sorting out of the symbology from the pictorial display. To counter this problem, the contrast between the two elements was increased by changing the G-80 software to make the symbols brighter than the picture elements. Although only two levels of brightness were available from the G-80, the level of each vector picture element could be set for one level or the other. The pictorial elements were set for low level, except for the landing pad. This helped some, but it seemed appropriate to implement a positive means for the pilot to accomplish mode selection. The method chosen was to install a beep switch on the collective stick which could be used to sequence mode changes as flight progressed. An up-down switch was used to enable changing to a previous mode. This arrangement proved acceptable for mode-change control.

The problem of sudden changes in the displayed information was compounded, all along, by the appearance (or disappearance) of detail in the expanding pictorial display. Because the G-80 has only two levels of brightness control, the added detail could not be faded in or out. It was found that a few approaches in the simulator would accustom the pilot to this idiosyncrasy. At this point in the development phase, it became possible to hover

the aircraft over the pad. There was a strong indication from human factors and project pilots that the following factors would require further consideration:

a. All information would have to be available on the CRT display.

b. The update rate was marginally adequate.

c. A heading-hold function would be needed to reduce workload.

d. The workload would not allow performance of the mission without further improvement of the displays and controls.

e. The ground-effect model produced an exagerated ground cushion, making it difficult to set the helicopter on the pad.

f. Touchdown velocities under 1.2 m/sec (4 ft/sec) were very difficult to achieve.

Scale Expansion Algorithm. The algorithm selected for scaling the radar image was originally a simple linear relationship, where the expansion took place as the inverse function of the aircraft altitude. The glideslope was entered into the function in order to maintain a realistic relationship between elements on the display. First, the glide path-ground intersection was selected at a point two-thirds the distance from the helicopter location symbol and the top of the display. Two glideslope values were selected (6° and 10°) as variables, and these values were applied to the algorithm. The scaling of the radar image at the zero-skid height end, was then defined as one where the 30.5 m x 30.5 m (100 x 100 ft) pad fills the display screen. For all other heights, the scaling algorithm was designed to keep the projected flight path (6° or 10°) intersection at a point two-thirds the distance from the helicopter symbol to the top of the display.

This arrangement maintains the correct geometric relationship so that a glide path intersects a fixed point on the display as the aircraft closes the distance to that point in the real world. All other points expand from the fixed point, providing a realistic cue as to where the aircraft path intersects the ground.

Everyone who tried the simulated display indicated a strong sensation of rapid loss of altitude as height decreased below approximately 61 m (200 ft). The sensation was so strong that a large recovery overshoot was always applied until a number of approaches were made and repeated experience offset the perceived height/velocity relationship. The sensation was aptly termed the "zooming" sensation and called for a good deal of discussion and speculation about the cause. First, the expansion algorithm was verified by observing the image size of the landing pad vs indicated height (for low altitudes the term height seems more appropriate and implies height-above-ground).

Observations by human factors pilots resulted in a conclusion, on their part, that the problem was directly related to the limited angular size of the display as seen by the pilot. The display is very limited as far as total field-of-view (FOV), as compared with the FOV the pilot normally uses to obtain visual cues. If real-world scaling were used for the display, the landing pad would expand so its edges would be far outside the screen as the aircraft neared the pad. Because the pad was limited in size to fit on the screen, even for zero wheel-height, the scaling was distorted. The distortion was such as to delay the greatest expansion of the landing pad until the height decreased below 61 m (200 ft).

The conclusion was that a different algorithm was needed to prevent the zooming sensation and to provide instead, a realistic sensation. Deviation from the original scheme would require some compromises. It was reasoned that the geometric relationship between glide path and the point of ground intersection becomes less important as the pilot nears the pad. One point of rationale is that the pilot will normally position the helicopter above the

center of the pad anyway and then let down. The concept of glide path becomes incongruent with the situation, once the helicopter reaches a point near the pad. To alleviate the problem, the algorithm could be bent at low altitudes. Accordingly, the algorithm was modified (both for the 6° and 10° slopes) by putting breaks in the curves at lower altitudes. Figure 4-4 illustrates the changes made. Breakpoints were made in both curves, which were originally straight lines, at 18 m (60 ft) and 3 m (10 ft) landing gear height. The apparent-height vertical scale represents a scale factor used by the G-80 graphics generator, where the zero end represents the point where the image stops expanding as the helicopter touches down, and the high end is a factor of an established maximum height value. The straight line portion (no compensation) represents a one-to-one correspondence with the real world as seen by the pilot. Two different curves were used, depending on whether the pad filled or half filled the screen at touchdown (discussed later).

Simulated flights indicated only partial relief from the zooming sensation. In order to establish a data point for judging effectiveness, the display with the modified algorithm was evaluated.

The control system, up to this point, was mechanized with an attitude-command, attitude-hold system for pitch and roll, and a rate-command rate-hold system in yaw (Reference 15). In view of the high pilot workload, it seemed appropriate to provide a heading-hold function to eliminate direction control from the total workload. This function was added, with high authority integral control, to handle the large power changes encountered when transitioning to hover. This allowed flight without the use of pedals, once the aircraft was lined up on approach. The ground-effect model was modified to a third-order curve fit approximation to create a more realistic effect. Tests showed improvement, but a small amount of vertical-velocity damping was needed to prevent over-control. Part of the problem was that the cockpit collective stick was not counterbalanced. Therefore, a large amount of friction was necessary to hold the stick vertically, causing a breakout friction level which was difficult to accommodate while precisely maintaining height. (This problem was eliminated after the formal test phase.)

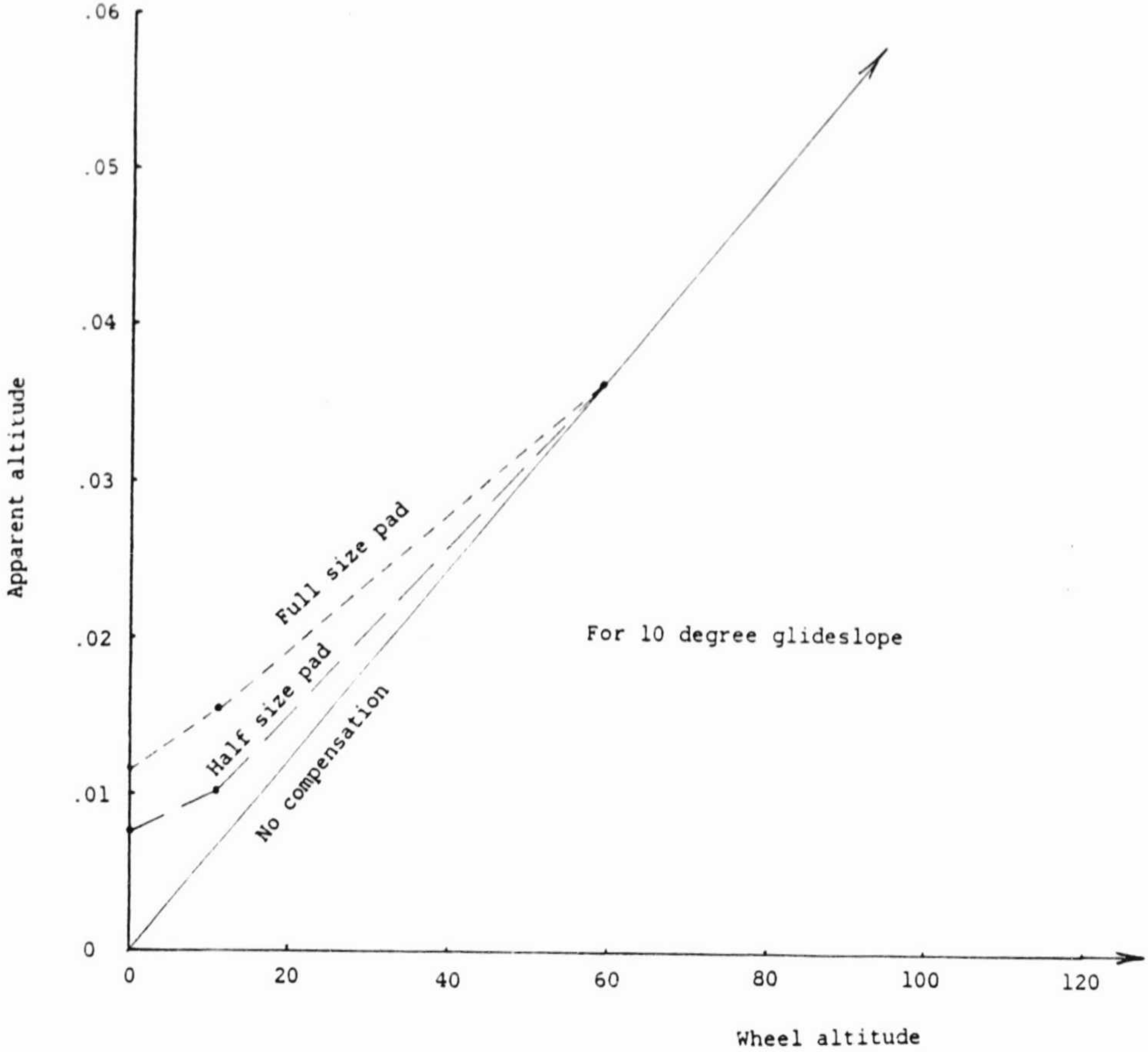

Figure 4-4. Scale expansion algorithm modification.

Horizontal velocity control was still a problem, and the following observations were pertinent:

a. Attitude changes, while maintaining hover, are so small as to be imperceptable on an attitude indicator. This implies that attitude control alone is not fundamental to hovering.

b. Ambiguity in interpreting cues may be a problem where restricted FOV displays are concerned.

c. More detail (texture) may be important in the pictorial display to allow resolution of ambiguity.

d. An important element is the contrast between that which is pictorial and that which is symbolic.

Symbolic Display Development. The task of developing the symbolic display elements was directed by the results of simulated flights and system/sensor considerations (References 7 and 15). Because a primary goal was to use cues provided by the pictorial display, as much as possible, it was important to provide only the needed supplemental symbolic cues. It was quickly evident in simulated flights that added symbology represents clutter, as far as the pictorial display is concerned. Again, this may result from inadequate contrast between the elements displayed, but it bears some weight, nevertheless. One factor driving the design was the need to place essential elements on the CRT display because scan-time is limited. Another factor was the large dynamic ratio over which the aircraft operates in decelerating from cruise flight to hover.

The first case in point was the symbology to present adequate height information. At higher altitudes a coarser scale is needed, while in hover, a much finer one is needed. This almost automatically precludes using a fixed-scale, moving-pointer arrangement because the range of sensitivity variation would require extreme compression of the top part of the scale. The moving-scale, fixed-pointer design was selected for test.

Sudden scale changes were avoided by using a nonlinear scale design. The scale is approximately logarithmic with an offset at zero wheel-height. Figure 4-5a illustrates the design. The triangular index is fixed on the screen vertical centerline. The scale moves vertically near the right edge of the screen. Figure 4-5b illustrates the low-end scale indication. Tests indicated this scale provides adequate information for the most part, but another symbolic cue was added to provide a very strong cue near wheel touchdown height [below 1.6 m (5 ft)]. This latter cue was provided by a horizontal line, with hash marks, representing the ground coming closer at touchdown. This additional cue reduced workload by eliminating the need to scan and read the height scale. Figure 4-5b illustrates the symbol, which coincides with zero altitude on the scale.

Figures 4-5a and b also illustrate the helicopter location or airplane symbol for horizontal-position reference. The horizontal-velocity control problem seemed to be caused by a combination of reduced indication sensitivity resulting from limited FOV, and by ambiguity in the available cues. When the helicopter translates vertically, the landing pad expands or contracts; a section of the landing pad near the helicopter appears to move horizontally just as if horizontal translation were taking place; therefore, there was confusion between whether vertical or horizontal operation was occurring because the cues were the same. This problem was thought to be aggravated by lack of texture in the pictorial display. In a real-world situation, if texture is sufficient, the texture will be seen to expand in all directions away from the point directly below the helicopter as it moves vertically. This allows the mental processes to resolve any ambiguity. As an experiment, some texture was added to the landing pad. Also, a landing pad which was smaller at touchdown was developed and tested. The small pad seemed to provide better scaling to reduce ambiguity effects. It was expected that the reduced sensitivity would result in degraded horizontal position and velocity control, but the result was an improvement. The indication was that ambiguity was a greater problem than sensitivity.

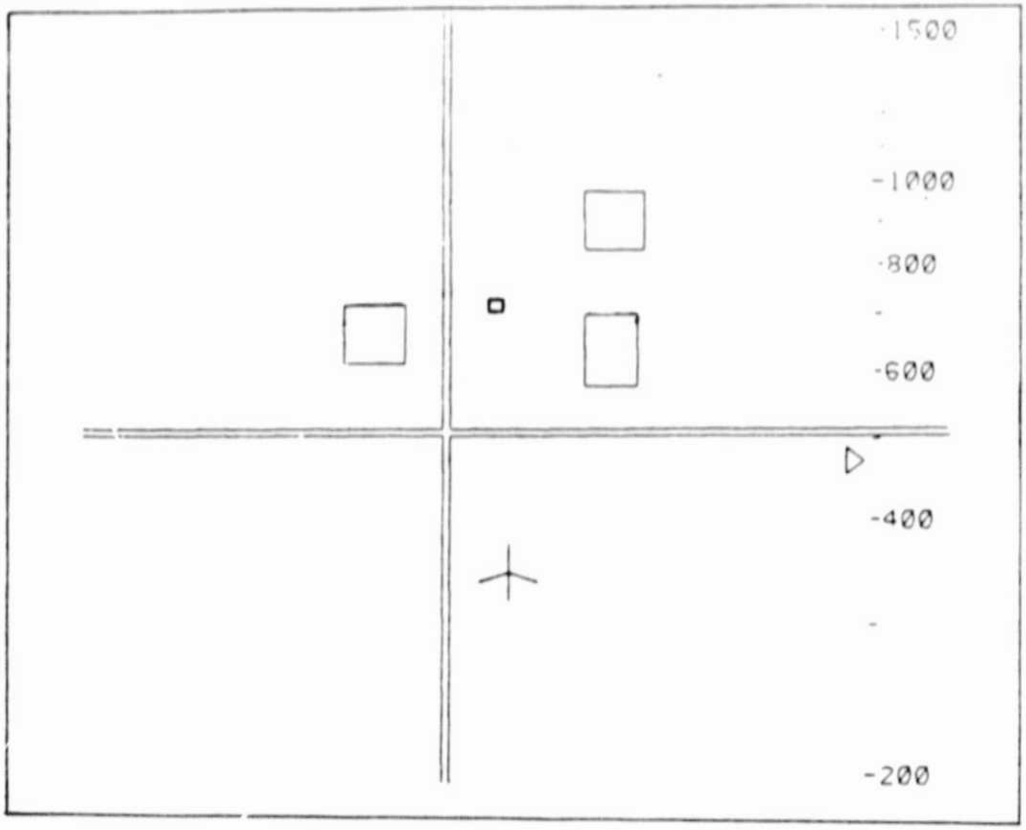

Figure 4-5a. Altitude scale - airplane symbol.

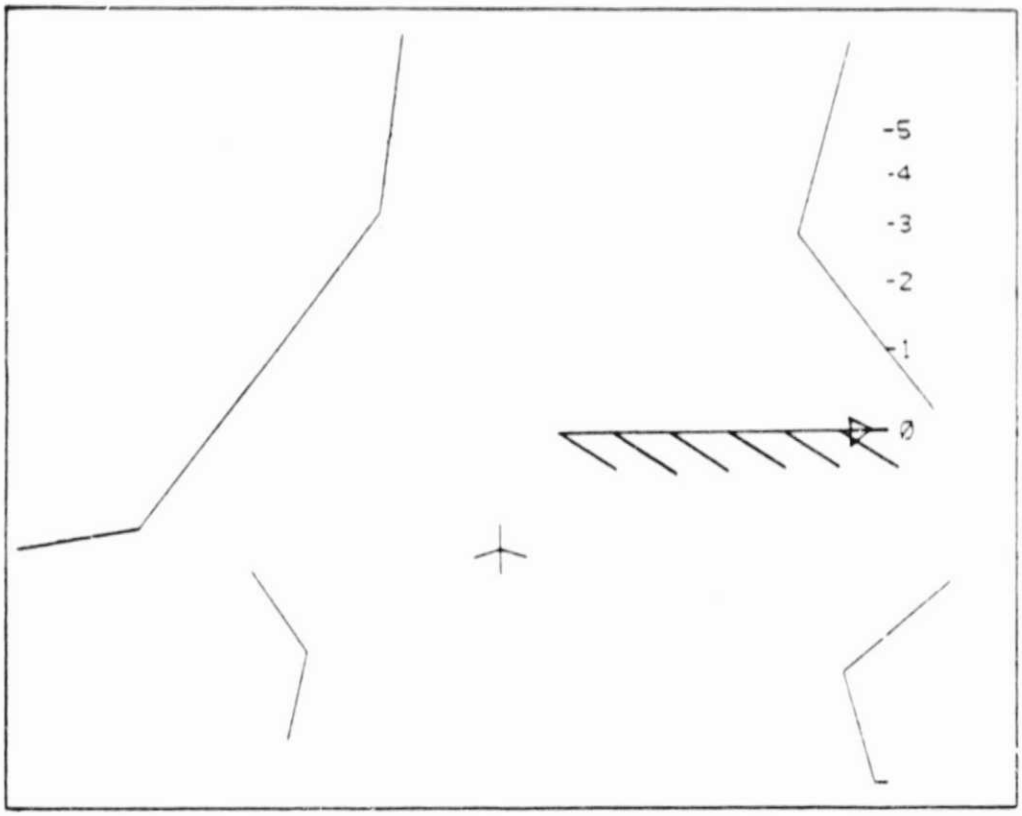

Figure 4-5b. Altitude scale - ground symbol.

It was decided to evaluate both a small and large pad and two levels of texture on the pad in the formal test phase. The texture is illustrated in Figure 4-6, which also shows the horizontal velocity and acceleration-vector symbology, that was provided in conjunction with the preliminary tests. This display provided a significant improvement in performance and associated reduction in workload. Figure 4-6 illustrates the symbology used in the formal test phase. The radial line extending from the helicopter location symbol is the ground-velocity vector magnitude and direction. The small octagon represents horizontal acceleration by its displacement from the tip of the velocity vector. The provision of this symbology in a candidate operational system would call for the sensing or deriving velocity information in addition to the imaging sensor. A doppler radar could provide direct measurement. Otherwise, beacon sensor data or a video tracker might be used, if smoothed by inertial sensors.

For deceleration control, it was determined that an airspeed scale would be useful on the CRT, along with an indication of where the flight path intersects the ground (References 5, 11, and 17). A scale was developed which appears on the CRT once airspeed decreases below 26 m/sec (50 knots) IAS. The scale was made to cover rearward flight, up to 5 m/sec (10 knots). Such an indication would have to be provided in the actual system by a low airspeed sensor with vector capability. Figure 4-7 illustrates the airspeed scale, which is a fixed scale with a moving triangular pointer. This figure also illustrates the curved-ground intercept cursor, a beacon indicator, a slip indicator, and a rate-of-descent, or instantaneous vertical-speed indicator (IVSI) with a pair of indices for descent control. The cursor represents the ground intersection of a 10° slope and was designed after a similar cursor used in the Reference 6 program. The slip indicator was designed to emulate a standard spirit type at the bottom of the screen. It was decided to drive the cursor with true aerodynamic slip angle, up to ±20°. This decision was based on hardware constraints and/or computer software development. We later concluded, based on pilot evaluation, that lateral acceleration is a better indice; however, sideslip was used because of its relative ease within the

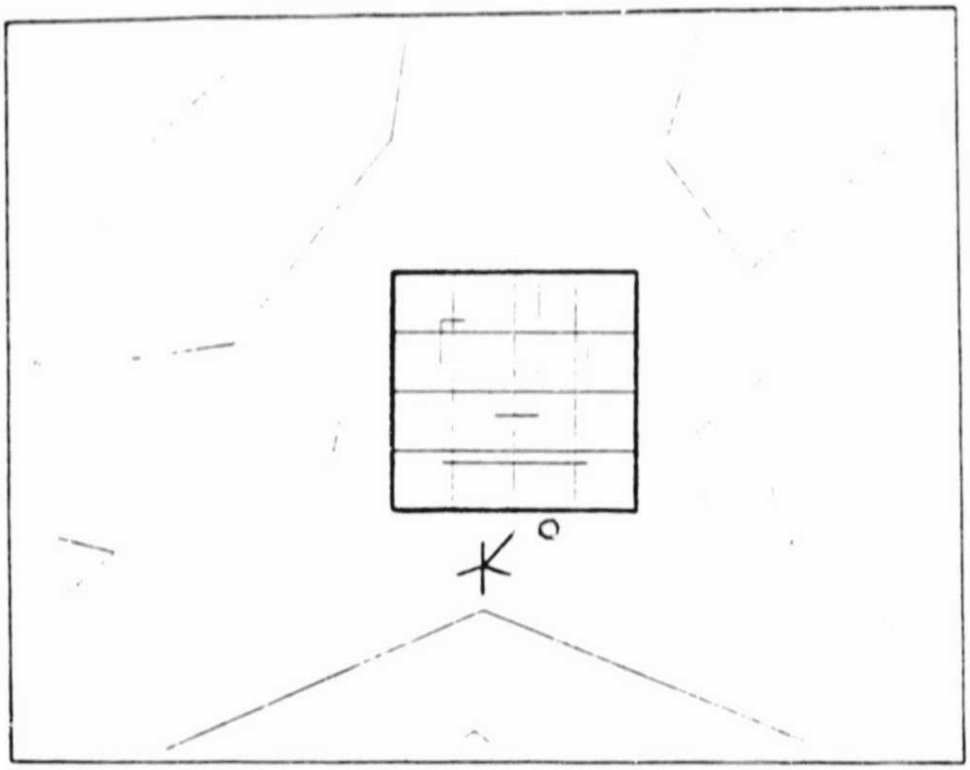

Figure 4-6. Texture on pad, velocity and acceleration vectors.

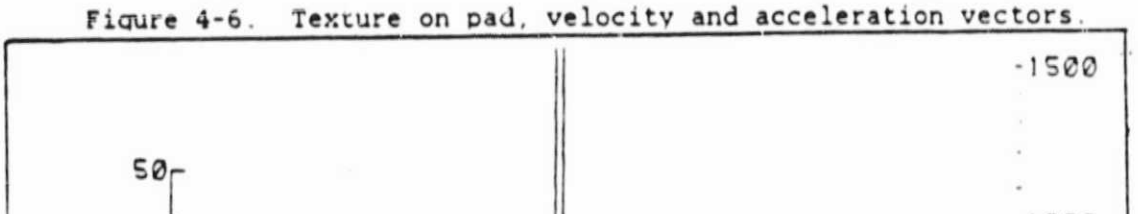

Figure 4-7. Airspeed scale and other symbols.

math modeling concept and lack of time to integrate lateral acceleration. Subsequent to the formal tests, a model was developed to directly emulate a lateral slip indicator. A short evaluation by a HFE pilot was made indicating this display to be acceptable.

The IVSI consists of a horizontal straight line which moves vertically relative to the fixed triangular index of the altitude scale. There was no scale provided, but instead, a pair of reference indices for indicating the ideal rate for the present speed was used to maintain the glideslope. Tests indicated the reference indices to be a useful function until very low forward speeds are reached. The motion of the horizontal indicator increases at low speeds because of the slope indication and in fact, becomes theoretically infinite at zero speed. Human Factors engineers considered it worthwhile to evaluate reference indices in the formal test phase. Figure 4-7 illustrates a beacon-indicating symbol which consists of an open-center cross centered on the landing pad. The beacon indicating symbol was designed to be located by means of a a 4-directional beep switch on the collective stick. The symbol was designed to appear on the screen by means of a command button on the CRT bezel. The pilots found that the beacon symbol served as an additional position reference during hover.

The pilots determined that the slip indicator was of little use near or at hover because of large excursions in the slip angle for very small vectorial speed changes. Therefore, the symbol was made to disappear as speed decreased below 8 m/sec (15 knots).

For the hover mode, a scaled reference was useful. To provide this reference, a stick-model of the helicopter was built to serve as the helicopter location reference. The model represents the actual length of the helicopter fuselage. The rotor tip path was included, but tests indicated it was not necessary and caused too much clutter. Figure 4-8 illustrates this symbol, along with a hover situation at zero height and an additional scale devised to show instantaneous vertical speed on a very sensitive scale. The values on the scale are in feet-per-second. This scale was developed to provide an additional cue to the expanding pictorial image.

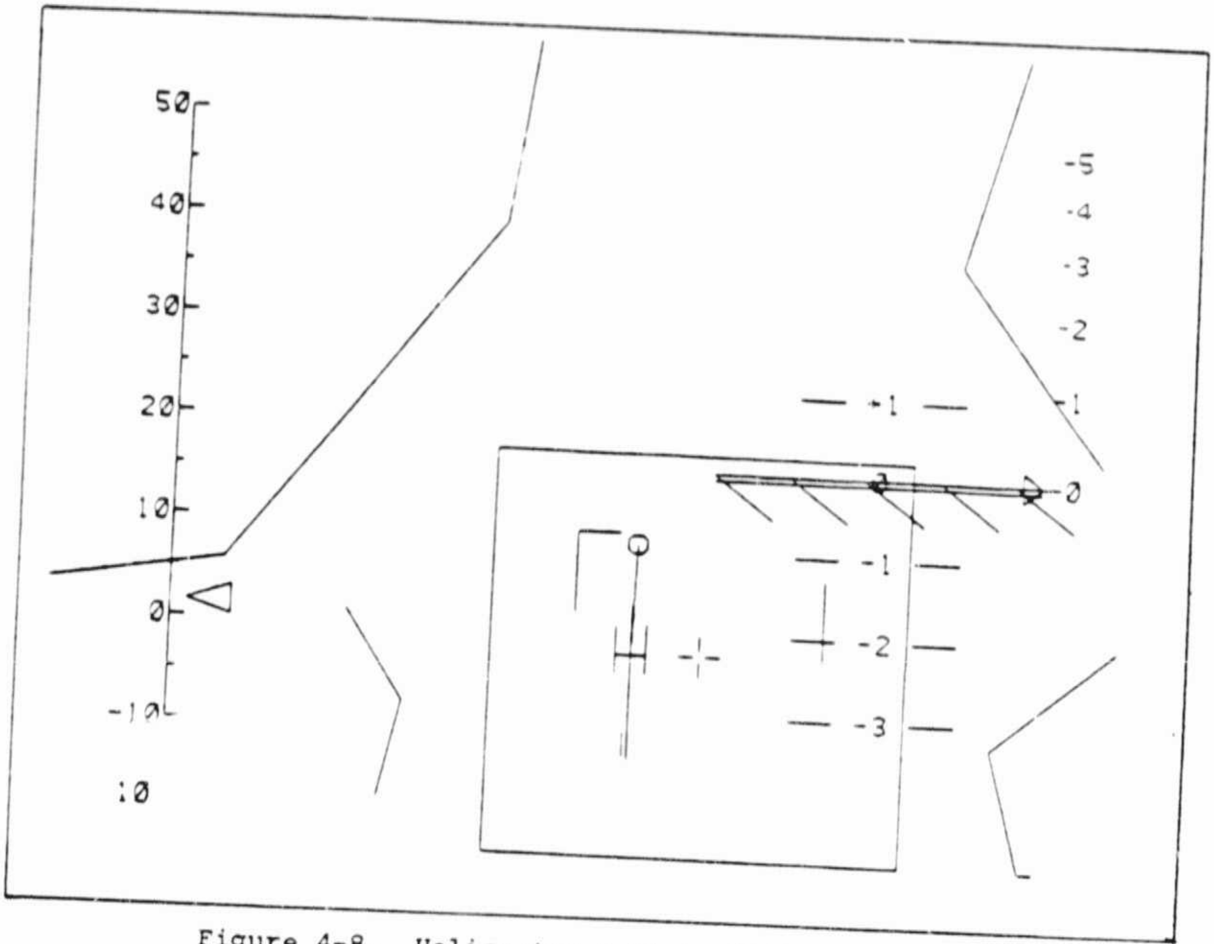

Figure 4-8. Helicopter symbol, IVSI scale.

To better illustrate the overall appearance of symbology on the CRT, photographs from the CRT display are shown in Figure 4-9. The three photographs represent a sequence starting with Figure 4-9a at an altitude of 286m (940 ft) and the aircraft approaching the outer end of the bridge. Figure 4-9b shows a condition near the pad at 20 m (65 ft) height and 4-9c shows the hover condition over the pad at about 2 m (6.5 ft). These photos illustrate the contrast used between the pictorial and symbolic display elements with the symbolic elements being the brightest. The pilots set their own deceleration profiles based on the situation information available from the pictorial display.

Figure 4-10 is a photo of the cockpit and instrument panel, showing the CRT on the right side directly in front of the pilot.

Mathematical Models

The mathematical model used to simulate helicopter flight was a version of the ARMCOP program, as provided by the NASA-Ames Research Center. This mathematical model was modified to include a ground-effect model. Early simulator flights indicated the desirability of adding the ground-cushion effect to aid in hover-height control. A second-order approximation was used and found to be adequate after adjusting the performance to meet a known horsepower savings criterion. Attempts were made to incorporate coefficients for the Bell Model 412 helicopter and to correlate the performance with flight test data and another model, the C81. However, the flight test data on the Model 412 helicopter was sparse and confidence in using it was low. The best overall data was available on the Bell Model 222B. In addition, control system work had been done using Model 222B, the flight simulator, and a mathematical model used internally at Bell. As a result, the decision was made to use the 222B as the basic helicopter model to be flown in the simulation. Objective and subjective comparisons between math models could then be made and, indeed, showed good correlation all across.

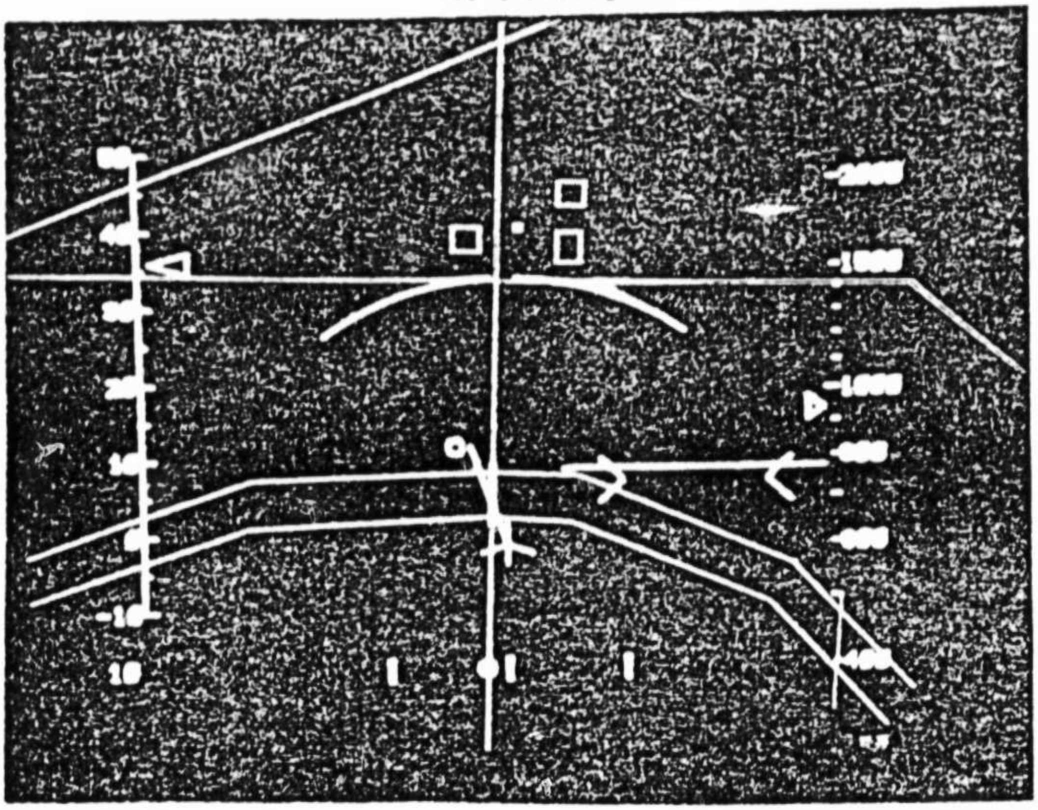

Figure 4-9a. Beginning deceleration.

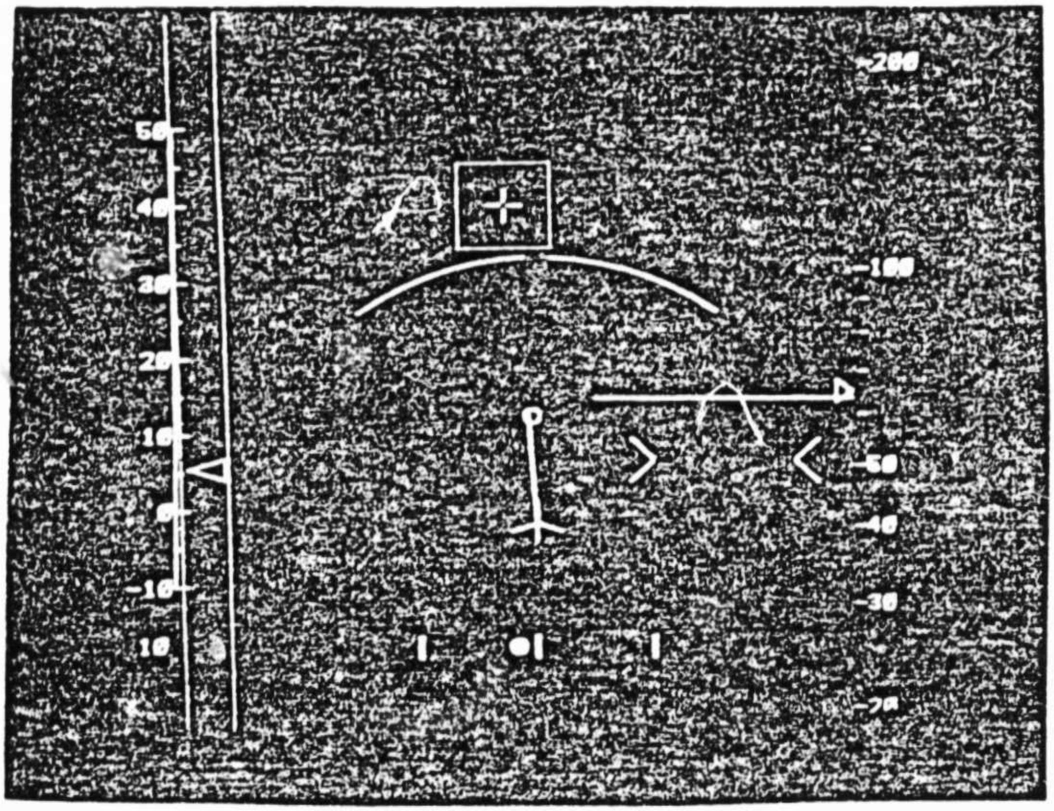

Figure 4-9b. Nearing pad.

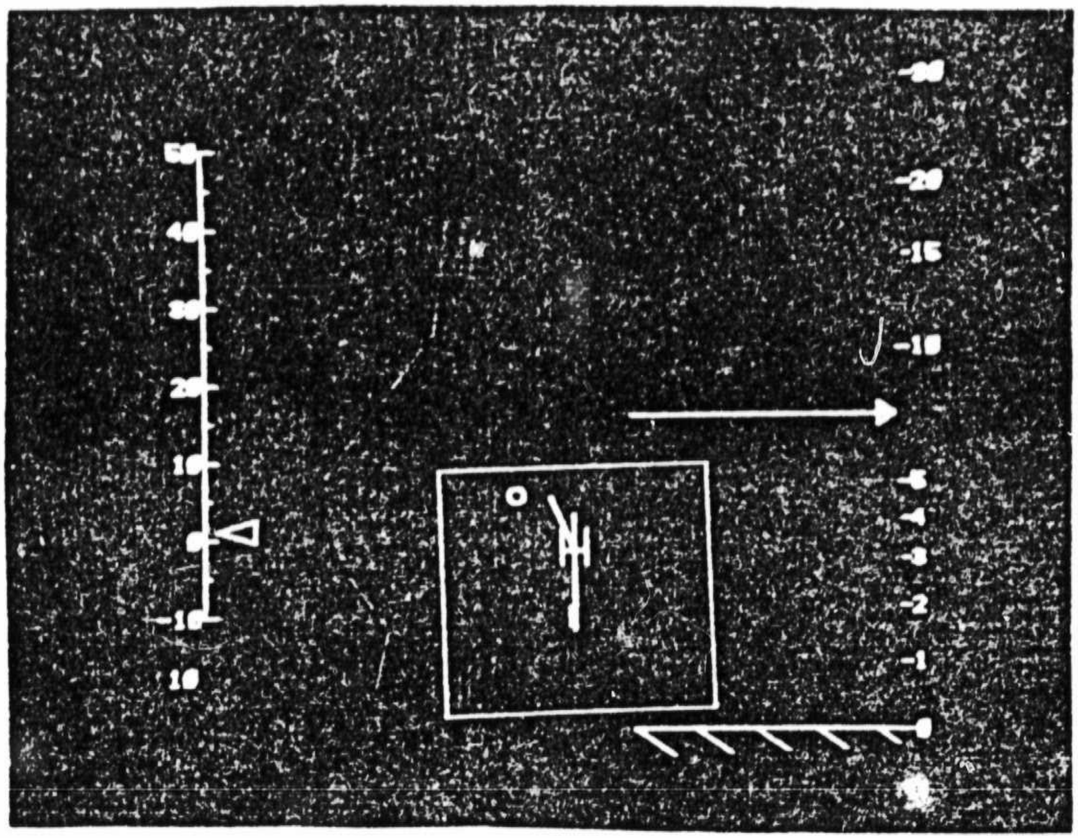

Figure 4-9c. Low hover display.

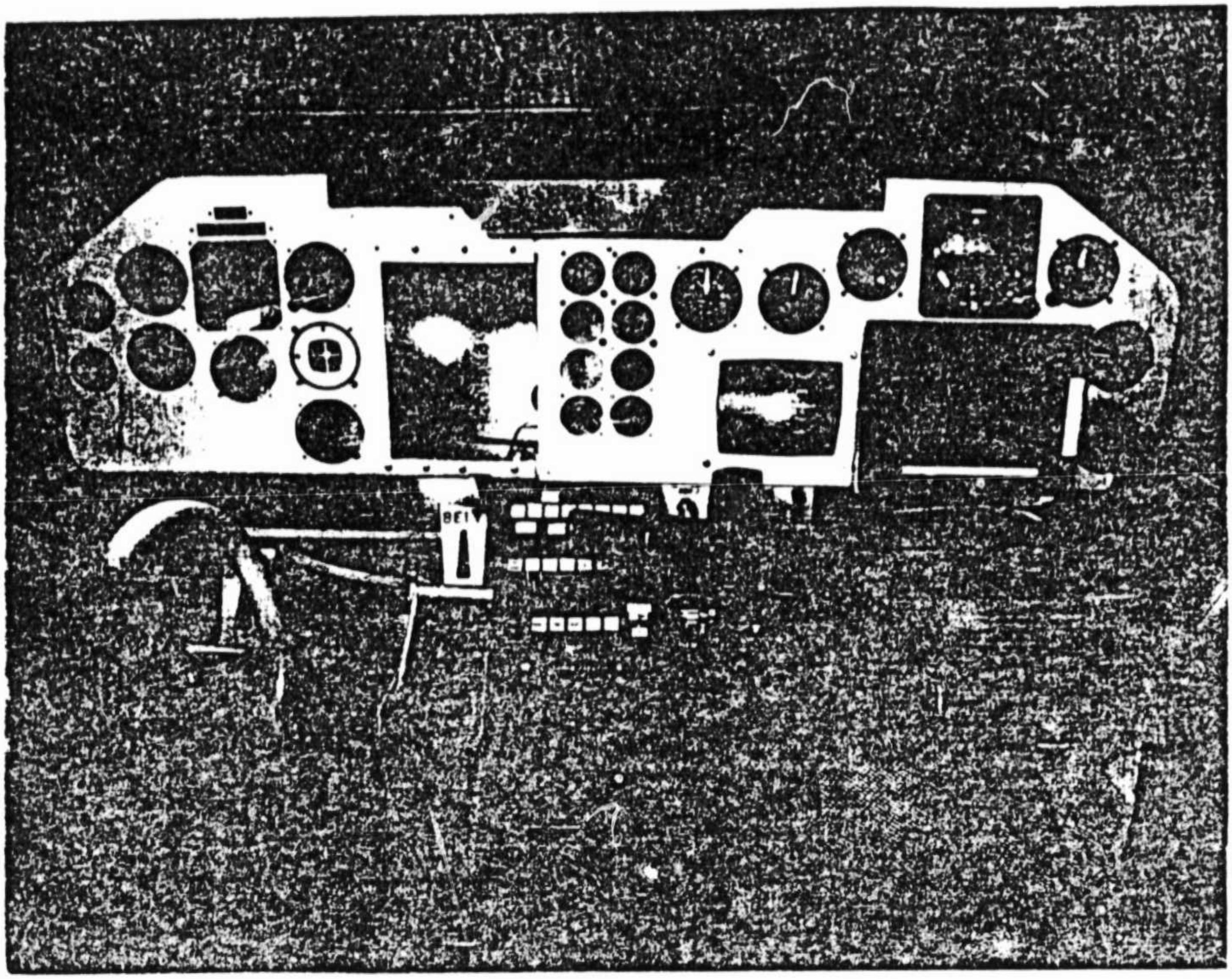

Figure 4-10. Cockpit and panel.

The ARMCOP program was run on the main computer (VAX) which was interfaced to the cockpit through I/O channels. A portion of the control system was modeled in an AD10 multiple-processor computer. (See Appendix A for the overall computing equipment setup.) The SCAS actuator model rate signals and pilot feed-forward quickening terms were processed in the AD10. This allowed the VAX to be unloaded to some extent. The attitude signals and references were processed in the VAX.

Control System

The control system was derived from a basic system which had been developed internally at Bell. During preliminary simulated flights, it was apparent that a rate-damped system would not suffice, as was implied from the literature search. Accordingly, an attitude-hold system was implemented and used as the basic control system. Two modes of operation were developed: an attitude-command and the other a rate-command mode. In the attitude-command mode, the helicopter attitude is directly proportional to stick displacement. In the rate-command mode, the angular rate of attitude is proportional to stick displacement. To keep the attitude from drifting, in the latter case, a threshold was needed in the stick motion from its trim position. It was found to be very difficult to achieve hover in the rate-command mode of operation, during simulated flights.

A rate-command heading-hold system was implemented (Reference 15). The cockpit did not have an actuator to provide pedal force trim. A centering spring without preload was the only feel provision. The lack of preload meant that releasing the pedals would cause them to move to within a fairly large band of positions. The rate-command position threshold was set at 1.25 cm (0.5 in) to keep the heading from drifting. This setting proved uncomfortable for maneuvering the helicopter and was not really satisfactory for cruise flight turning. For the purposes of this test program, the heading-hold system maintained heading throughout the entire deceleration and hovering maneuver. Adequate gains and error integration feedback were set to keep the

heading error small (<3 degrees) during the transition to hover. The collective control was provided a small amount of pure velocity feedback to reduce its sensitivity in hover.

During this development phase, the gains and time constants were adjusted based on pilots subjective evaluation, as well as time-history response traces. During the experimental period, it was observed that the horizontal-velocity response of the helicopter could be quickened by using an attitude response which included an initial overshoot caused by feed-forward terms in the control laws. The quickened response seemed to improve the hover performance markedly. However, the attitude excursions were considered too large by Human Factors pilots, especially when considering what the effect would be in a situation with a moving-base simulator or actual aircraft. The unatural response to stick motion was considered to be too objectionable. Consequently, the overshoot was decreased to a compromise level. More detail regarding the control system is contained in the TEST PLAN (Appendix A) and Appendix B, which contains gain factors and response plots.

5. EXPERIMENT CONDITIONS

Simulation Equipment

This section describes and defines the CRT symbols and other equipment in the cockpit that were used as pilot aids to successful completion of the task during the formal test phase of this program.

Cockpit Equipment. The cockpit and its equipment are described in the program test plan. (See Appendix A of this report.) The test plan describes the simulation setup, cockpit display equipment, and flight control system. General descriptions of the display symbols are also included. Appendix B includes details of the control system responses.

CRT Symbols. The rationale for the selection of each symbol, as defined herein, is a result of the literature review concerning previous experiments and the extensive evaluation of different symbol configurations during the development and pretest phases of this experiment. The various symbol sets and equipment packages presented to the test subjects during the experiment were purposely selected to represent the full range of configurations previously evaluated.

The following pages contain illustrations and descriptions of the various symbols, on an individual basis. The cockpit CRT had a bezel which obscured a small portion of the display. The graphic generation system was set to present data on 82% of the CRT display, and to use a pixel map of dimensions 500 vertical by 700 horizontal elements. This 500 by 700 pixel area was defined as the useful CRT screen area, which amounted to an actual area 11 cm (4.5 in) by 13.5 cm (6.3 in).

Aircraft Position Indicator. An aircraft symbol and a helicopter symbol were selected to represent position indications on the CRT (Figure 5-1a and b). It was determined during the pretest phase that the placement of the aircraft symbol on the CRT affected pilot performance as described in Section 4. When

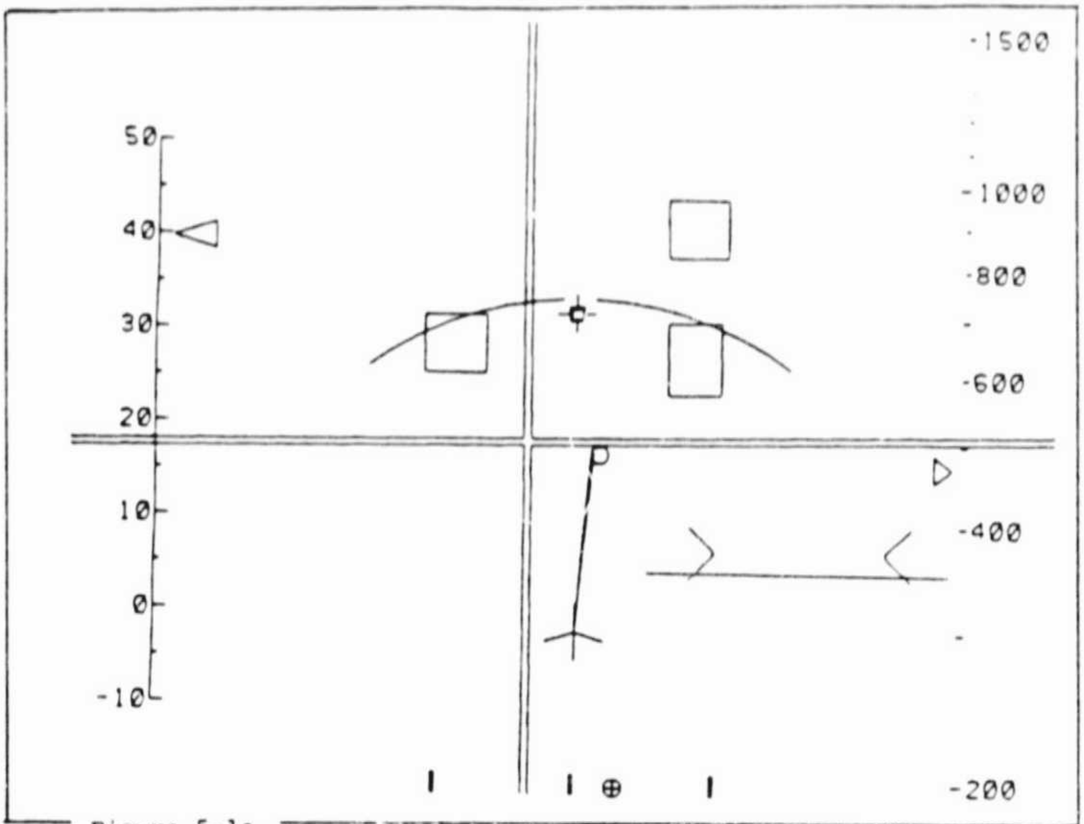

Figure 5-1a.

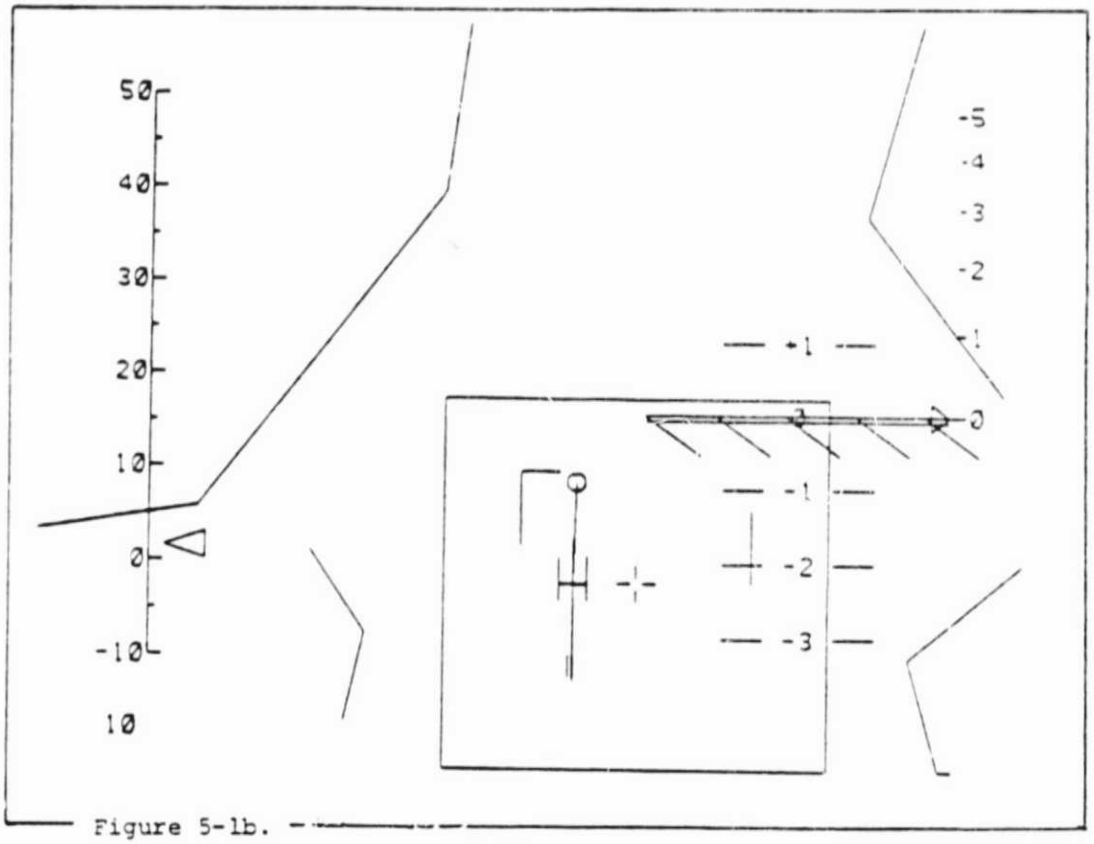

Figure 5-1b.

Figure 5-1. CRT symbols.

the aircraft position indicator was relocated to a position 25% up from the lower edge of the CRT, the control reversal problem disappeared along with the outside looking-in syndrome. Either the aircraft or the helicopter position indicator was available in all configurations and modes.

Radar Altitude Scale. Radar altitude was presented on the right side of the CRT (Figures 5-1a and b) by means of a rolling, nonlinear scale with a fixed-index pointer. The rolling scale presentation was selected to facilitate a large enough increment between different altitudes to allow rate information to be apparent. The nonlinear scale was selected to present the most detailed altitude information close to the ground, where precise altitude control is necessary for a stable hover. The nonlinear scale is defined as follows:

0 to 5 feet, in 1-foot increments
5 to 20 feet, in 5-foot increments
20 to 100 feet, in 10-foot increments
100 to 200 feet, in 50-foot increments
200 to 1500 feet, in 100-foot increments
1500 to 2000 feet, in a 500-foot increment

The extent of the scale was defined as full screen height. If altitude increased above 610 m (2000 ft) AGL, the radar altitude scale was blanked from the screen because of the predicted radar altimeter sensitivity. The radar altitude was available in all modes of flight below 610 m (2000 ft) AGL.

Vertical Speed Indicator and Command Pointers. In addition to a rate of climb/descent discernable from the rolling altitude scale, a vertical speed indication (Figure 5-1a) was presented by means of a horizontal line drawn on the right side of the CRT immediately to the left of the radar altitude scale. Vertical speed information was shown as a direct function of the horizontal line and line movement was associated with the index pointer of the radar altimeter. The vertical speed indication was directional and linear in movement with zero rate of climb indicated when the line was adjacent to the rada altimeter index pointer.

The vertical speed command pointers were a pair of fixed indices located immediately to the left of the radar altitude scale and below the radar altitude index pointer. The command pointers were available in the approach and transition modes of all configurations and worked in conjunction with the vertical speed indicator to show an ideal descent rate for the selected glide slope angle and forward speed. Because the command pointers were in a fixed location on the CRT, the sensitivity of the vertical speed indicator was adjusted to command the necessary changes in rate of descent as the aircraft ground speed and altitude decreased throughout the approach maneuver. After the proper approach path had been intercepted, if the vertical speed index remained centered on the vertical speed command pointer, then the aircraft was assumed to be approaching along the proper glidepath. Upon selecting the hover mode, the sensitivity was fixed and the command pointers were eliminated because the vertical speed sensitivity would tend toward infinity at zero speed. The maximum sensitivity was limited to the value used with expanded vertical speed scale.

Glideslope Cursor. The glideslope cursor (Figure 5-1a) was depicted as an arc in a fixed location above the aircraft symbol. This symbol was used to indicate interception of the desired approach angle with the landing spot. If the pilot kept the cursor centered on the intended landing spot the helicopter would be on the glideslope. If the landing spot drifted below the cursor the helicopter would be high on the glideslope, and if the landing spot drifted above the cursor, the helicopter would be low on the glideslope. The glideslope cursor was available in all configurations when the approach or transition modes were selected.

Expanded Vertical Speed Scale. A numerical designation (Figure 5-1b) of rate of ascent/descent in feet per second was present on certain configurations in the transition and hover modes (see Table 5-1). The feet per second range of the scale was selected as one that would allow acceptable touchdown velocities from hover mode. The extent of the scale was from 17% to 62% of the CRT screen.

TABLE 5-1. CONFIGURATION MATRIX

Mission Aids	Configuration Code										
	[1]1	2	[1]3	[1]4	5	6	7	8	9	10	11
Radar altitude scale	X	X	X	X	X	X	X	X	X	X	X
Vertical speed scale	X	X	X	X	X	X	X	X	X	X	X
Vertical speed command pointer	X	X	X	X	X	X	X	X	X	X	X
Glideslope cursor	X	X	X	X	X	X	X	X	X	X	X
Aircraft position cursor	X	X	X	X	X	X	X	X	X	X	X
Helicopter symbol									X	X	X
Acceleration vector							X	X	X	X	X
Velocity vector							X	X	X	X	X
Wind speed and direction				X	X	X	X	X	X	X	X
Beacon	X	X	X	X	X	X	X	X	X	X	X
Airspeed	X	X	X	X	X	X	X	X	X	X	X
Expanded vertical speed				X	X	X				X	X
Slip	X	X	X	X	X	X	X	X	X	X	X
Pad 1/2 screen	X	X		X	X		X		X	X	X
Pad full screen			X			X		X			
Minimum texture	X			X			X			X	
Maximum texture		X	X		X	X		X	X		X
Micro-HUD											X

[1]Configurations 1, 3, and 4 were used in pretest but were not included in the formal evaluation.

Helicopter Symbol. The alternate representation of aircraft position evaluated was a helicopter symbol (Figure 5-1b) located 25% from the lower edge of the CRT. This symbol was available only during specified configurations (see Table 5-1) and then only in the transition and hover modes. The symbol was designed to represent a stick model helicopter (plan view). The size was scaled to match a Bell 222B and to match the 30.5 by 30.5 m (100 by 100 ft) pad-size scaling with the helicopter at zero skid height.

Airspeed. True airspeed was presented on the left side of the CRT using a linear fixed scale with a moving index pointer (Figures 5-1a and b). Because this experiment dealt only with the final approach portion of the mission, it was determined that the airspeed presented would be 26 m/sec (50 knots) through -5 m/sec (-10 knots). Airspeed rate and trend information were readily apparent by the direction and speed of the moving index pointer. At any time during the approach, if airspeed exceeded 26 m/sec (50 knots) forward or 5 m/sec (10 knots) rearward, the airspeed scale would disappear from the CRT, alerting the pilot that the helicopter was outside the design envelope of the experiment. The extent of the scale was set at 1[illegible] to 98% of the CRT screen.

Velocity and Acceleration Vectors. A line (Figure 5-1a) radiating from the center of the aircraft symbol was displayed on the CRT to provide velocity information. The line is a vector representation of ground velocity. The magnitude is proportional to velocity and the angle represents direction of motion. Aircraft acceleration was presented by a small circle, symbolic of the vector value of acceleration, with the center of the circle representing the end of the vector. The origin of the acceleration vector is the tip (or rather, the end) of the velocity vector. The scaling of both vectors was made to change with altitude, providing higher sensitivity for hover and keeping the vector available for use at higher altitudes. The scaling changes were controlled by altitude and were limited so that extreme values would not be encountered. Below 5.2 m (17 ft) altitude the scaling was limited to 6.3 cm/ft/sec (0.25 in/ft/sec) and 7.62 cm/ft/sec (0.3 in/ft/sec). Above 188 m (617 ft), the scaling was 0.343 cm/ft/sec (0.0135 in/ft/sec) and 0.457 cm/ft/sec (0.018 in/ft/sec). Table 5-1 lists the configurations in which the velocity and acceleration vectors were used.

Beacon. A beacon (Figure 5-1a and b) or corner reflector symbol, represented by a fixed size open cross, was placed approximately in the center of the landing pad. Use of the beacon in all modes and configurations was a pilot option that was selected from a pushbutton on the bezel of the CRT. The beacon was incorporated into the display to present landing pad location at extended range, and also assisted in determining movement over the pad while at a hover.

Slip. A computed slip angle representing the angle of the relative wind off the nose of the helicopter was depicted by a moving ball (Figure 5-1a) and three indices at the lower center of the CRT. The slip angle represented by the indices was 20° left or right of the centerline of the aircraft. When true airspeed decreased below 7.7 m/sec (15 knots), the slip symbology was made to disappear from the CRT.

Landing Pad 1/2 Screen. For this experiment, a landing pad, 30.5 m (100 ft) square, was represented using an expanding scale in all configurations during approach, transition, and hover modes. The pad 1/2 screen designation indicates that the landing area fills half the CRT (Figure 5-1b) when the aircraft is on the ground and becomes smaller in size as the aircraft gains altitude. The expansion of the pad, as altitude decreases, was controlled by an algorithm described in Figure 4-4, arrived at during the development phase of this program. The linear features on the landing pad represent minimum textural details. The configurations using the 1/2 size pad are listed in Table 5-1.

Pad Full Screen. Another method of illustrating the landing area in specified configurations was to allow the pad expanding scale to fill the entire CRT at touchdown. This full-scale pad (Figure 5-2) was presented to allow comparative evaluation between the increased sensitivity associated with the larger pad and the added CRT clutter effect associated with more lines on the CRT at low altitudes, when the maximum texture was used.

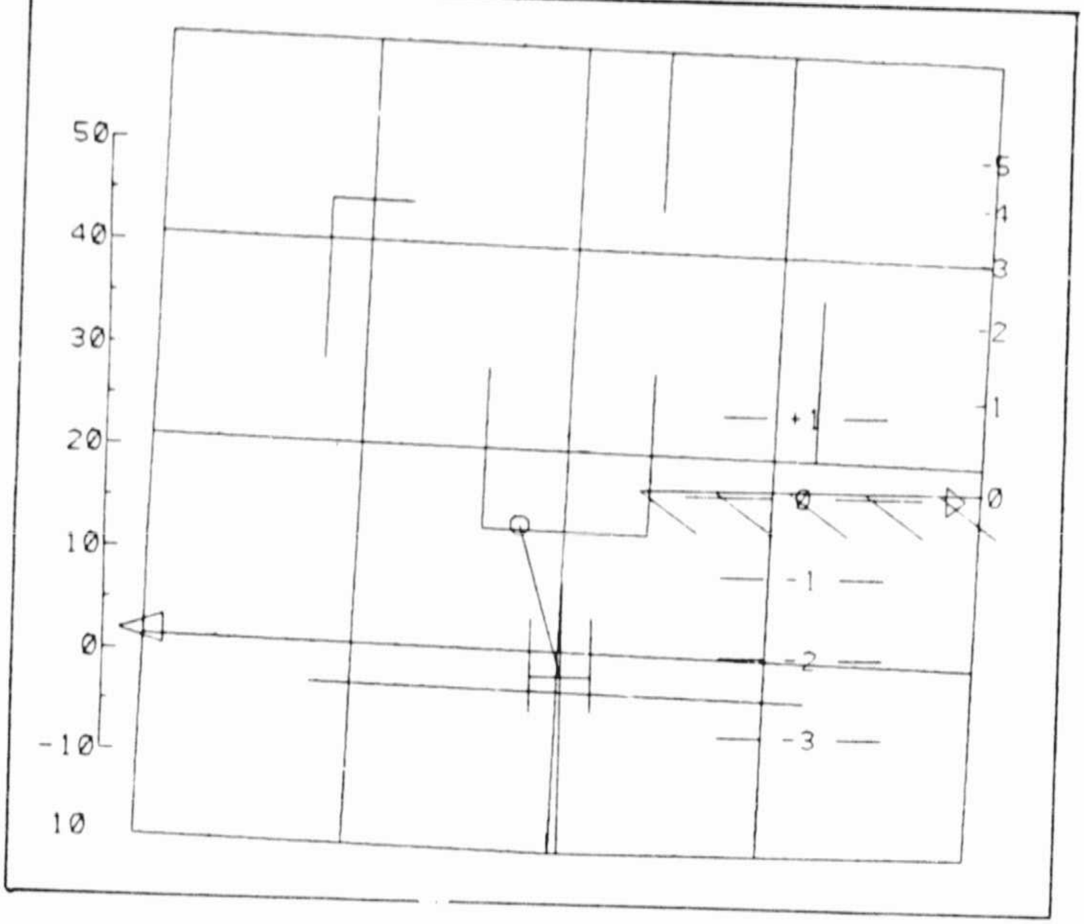

Figure 5-2. Full screen landing pad.

The maximum texture display has enhanced resolution and was designed to allow detection of helicopter movement while maneuvering close to the ground, more readily than a minimum-texture display would allow. The amount of texture presented was a function of helicopter radar altitude above the landing pad. The added grid lines and line features appeared as altitude reduced below 76m (250 ft). The configurations using the full size pad are listed in Table 5-1.

Micro-HUD. An optical device attached to a pair of eyeglasses (see Appendix A, Figure 26) that presented the pilot with an artificial horizon was used in one configuration of the experiment. Because there was no horizon reference presented on the CRT, the Micro-HUD was used to present aircraft attitude information. The Micro-HUD was used only in configuration 11 (see Table 5-1).

Subjects

The subjects who participated in this experiment consisted of five Bell Helicopter Textron test pilots and one NASA-Ames test pilot. The average number of years as a test pilot was 15.2, the average age was 41.8, and total flight time averaged 7000 hours of which the average rotary-wing flight time was 6262 hours. All subjects held a current commercial helicopter rating. Five of the six subject pilots had a commercial airplane rating and five of the six had certified flight instructor ratings.

The requirement of this experiment to focus on subjective rather than objective data, led to a stratified selection of test pilot subjects. Those pilots selected were known to express their opinions and make evaluations of experimental design concepts. From the first introductory briefing, each subject pilot was made aware of the fact they were evaluating a preliminary design, and any comments or suggestions they might have for improving the system would be appreciated.

Test Matrix

Formal test phase was preceeded by an average of 7.1 hours of familiarization and training for each subject. The training configurations were designed to allow each subject to become familiar with all of the mission aids and CRT symbology before beginning formal testing. As training periods progressed and more proficiency was gained by each subject, different mission aids were removed from the CRT to prepare the subjects for the minimum acceptable degraded capability configuration that would be flown during the formal test. After each subject satisfactorily completed two or three approaches using the training configurations, they were ready to proceed with the formal test phase.

Formal testing consisted of six different symbology configurations and two different sets of control laws. The criteria for selecting these different configurations took into consideration pilot workload to accomplish the task; CRT display complexity; anticipated implementation cost of each mission aid; programming and software limitations; and hardware limitations associated with both the aircraft model and the graphics generation equipment.

It was determined during development of the simulator system that pilot workload, system cost, and display complexity were inversely proportional up to a point, after which the workload increased resulting from difficulty in interpretation and added clutter. Because the main objective of this experiment was to evaluate different mission aids and control laws, the six test configurations were designed to represent a range of mission aids from the minimum necessary to complete the approach to one that employed more aids than could continually be monitored by the test subjects. This intentional selection of a broad band of categories was necessary to validate the usefulness of each mission aid both singularly and as it functioned in conjunction with other aids. The small sampling of test subjects was a factor determining the number of test configurations selected. The greater number of configurations reduced the statistical potential for individual bias to effect the validity of the results. The Configuration Matrix is shown in Table 5-1 and the Primary Test Conditions are shown in Table 5-2.

TABLE 5-2. PRIMARY TEST CONDITIONS

Mission Aids	Modes					
	Cruise	Entry	Approach	Transition	Hover	Other
Radar altitude scale	Fixed 2.5	Fixed 1.5	Expanding	Expanding	Expanding	
Vertical speed scale			X	X		
Vertical speed command pointer			X	X		
Glideslope cursor			X	X		
Aircraft position cursor	X	X	X	X	X	
Helicopter symbol				X	X	In selected modes will replace aircraft symbol
Acceleration vector			X	X	X	Not available in approach mode in configuration C-12
Velocity vector			X	X	X	Not available in approach mode in configuration C-12
Wind speed and direction	X	X	X	X	X	
Beacon	X	X	X	X	X	Separate switch function as selected by pilot
Airspeed	X	X	X	X	X	

TABLE 5-2. (Concluded)

Mission Aids	Modes					
	Cruise	Entry	Approach	Transition	Hover	Other
Expanded vertical scale			X	X	X	
Slip	X	X	X	X	X	
Pad 1/2 screen				X	X	Must be selected prior to commencing flight
Pad full screen				X	X	Must be selected prior to commencing flight
Minimum texture	X	X	X	X	X	Must be selected prior to commencing flight
Maximum texture	X	X	X	X	X	Must be selected prior to commencing flight
Micro-HUD	X	X	X	X	X	Separate piece of equipment

A Condition Sequence Schedule for each test subject is presented as Table 5-3. This schedule was created using a table of random numbers assigned to each approach configuration. The only constraints maintained during the creation of this schedule were to have control laws remain consistent and to fly consecutively all of the configurations that use a full screen pad on touchdown.

Data Acquisition

Both objective and subjective data was collected throughout the training and formal testing phases of the experiment. A system was devised to automatically record the following objective data at the termination of each approach.

a. Vertical touchdown velocity

b. Lateral touchdown velocity

c. Forward touchdown velocity

d. Touchdown pitch attitude

e. Touchdown roll attitude

f. Touchdown heading in relation to a desired reference

g. Position of touchdown in relation to the center of the pad

h. Date and time of touchdown

i. Name of subject

TABLE 5-3. CONDITION SEQUENCE SCHEDULE

	S1	S2	S3	S4	S5	S6
1	A-7	R-10	R-8	A-6	A-8	R-7
2	A-9	R-11	R-10	A-8	A-9	R-11
3	A-2	R-7	R-7	A-7	A-7	R-9
4	A-10	R-9	R-9	A-9	A-10	R-10
5	A-11	R-2	R-11	A-10	A-2	R-8
6	A-6	R-8	R-2	A-11	A-11	R-6
7	A-8	R-6	A-7	R-10	R-11	A-8
8	R-6	A-6	A-10	R-9	R-7	A-6
9	R-8	A-8	A-11	R-11	R-10	A-7
10	R-7	A-10	A-9	R-7	R-2	A-10
11	R-2	A-2	A-2	R-6	R-9	A-9
12	R-10	A-9	A-8	R-8	R-8	A-11
13	R-9	A-7				
14	R-11	A-11				

A indicates attitude command controls
R indicates rate command controls
2-11 indicates symbol configuration
S indicates subject

j. Total time to complete the approach

k. Radar symbology mode

l. Control system being flown

In addition to objective data, an experimenter pilot (Human Factors pilot) recorded ground track, approach time, and hover time for each approach during the formal test phase.

Subjective data was recorded using two different methods. The first method used the Subjective Simulator Evaluation Questionnaire. During the formal testing, the subject pilots recorded their comments after each configuration. During the training phase and while the formal configurations were being flown, subject pilot comments were recorded by the experimenter pilot. The latter method of recording pilot comments during their simulator flight may have provided the experimenters with the most valuable subjective data in relation to the genuine opinions of the subject pilots.

6. DATA ANALYSIS

Data was collected for a number of experimental configurations. For the formal test phase, configurations were selected to provide a cross section of those configurations evaluated during preliminary (pretest) simulation flights. Six configurations, Numbers 2, 7, 8, 9, 10, and 11 (see Table 5-1) were selected for evaluation. Appendix A contains a detailed description of the configurations and Table 5-1 depicts a configuration matrix showing the major differences between the configurations.

All eleven configurations included the following: radar altitude scale, vertical speed scale, vertical speed command pointer, glideslope cursor, aircraft position cursor, beacon, airspeed indicator, and slip indicator. Of the eleven configurations, six were selected for formal evaluation beginning with Number 2, the least complex:

a. Configuration Number 2 did not include a helicopter symbol, acceleration vector, velocity vector, wind speed direction, the expanded vertical speed, pad 1/2 screen, minimum texture, or the Micro-HUD.

b. Configuration Number 7 did not include the helicopter symbol, the expanded vertical speed, pad 1/2 screen, maximum texture, or the Micro-HUD.

c. Configuration Number 8 did not include the helicopter symbol, the expanded vertical speed, 1/2 pad screen, minimum texture, or Micro-HUD.

d. Configuration Number 9 did not include expanded vertical speed, pad full screen, minimum texture, or the Micro-HUD.

e. Configuration Number 10 did not include pad full screen, maximum texture, or the Micro-HUD.

f. Configuration Number 11 did not include the pad full screen or minimum texture. It was the only configuration using the Micro-HUD.

The objective touchdown data for x, y, and z velocities; pitch and roll deviations; x and y touchdown deviations; and approach time for each test subject on each approach were all plotted and evaluated. A nonparametric sum of ranks was used on the data (see References 18 and 19). Table 6-1 shows the mean of all test subject touchdown data for each approach configuration and flight control system. The second column in Table 6-1 denotes the number of subjects flying a particular configuration. The x, y, and z touchdown velocities are measured in feet per second. The pitch and roll deviations represent a variance in degrees from an established pitch and roll attitude at a stationary hover 1/2 inch above the ground. The N/S and E/W touchdown deviations are measured in feet representing distance from the center of the landing pad. Because heading was held automatically, no heading deviation was used. Approach time is designated in minutes and tenths. To arrive at some quantitative rating for each approach configuration an average of the means was established excluding approach time (see References 18 and 19). These data indicate that configuration R-10 produced the lowest overall touchdown deviations from the optimum shown in Table 6-1.

Information from the Subjective Simulator Evaluation Questionnaires was assigned a numerical value to determine an order of preference. As Figure 6-1 illustrates, configuration R-8 was rated most desirable. The values shown in the figure are the mean of all the subject pilot ratings for each approach configuration. In addition to evaluating each approach configuration, the questionnaire data was also used to evaluate the individual mission aids (see Figure 6-2).

In addition to the evaluation of quantitative and subjective data to determine the best performance and most preferred configurations, the quantitative data was reevaluated against maximum acceptable criteria, or rather, deviation values, for the following parameters:

TABLE 6-1. MEAN TOUCHDOWN DATA

Config	S_S	V_Z	V_X	V_Y	P/D_V	R/D_V	$N\text{-}S/D_V$	$E\text{-}W/D_V$	T_M
R-2	4	0.5	3.6	2.1	1.1	0.2	16.0	13.0	6.8
A-2	6	0.3	1.5	3.7	1.0	0.8	8.5	7.8	5.0
R-7	6	0.4	0.4	0.4	0.5	0.2	3.4	3.2	5.2
A-7	6	0.6	1.0	0.4	0.4	1.1	3.9	4.8	4.9
R-8	6	0.6	0.4	0.5	0.4	0.2	4.2	4.6	5.6
A-8	6	0.5	0.5	0.9	0.4	0.8	3.2	2.5	5.3
R-9	6	0.6	0.4	0.4	0.6	0.1	5.9	2.4	5.2
A-9	6	0.7	1.1	0.6	1.0	0.8	5.2	2.7	5.4
R-10	6	0.6	0.2	0.3	0.5	0.1	2.8	1.9	5.3
A-10	6	0.4	0.9	0.4	0.8	0.6	8.7	3.4	5.0
R-11	5	0.5	0.7	0.6	0.3	0.2	7.8	2.1	5.3
A-11	4	0.6	0.4	0.3	0.8	0.5	4.7	3.9	6.3

Code

R	rate
A	attitude
S_S	subjects
V_Z	vertical touchdown velocity
V_X	fore/aft touchdown velocity
V_Y	lateral touchdown velocity
P/D_V	pitch deviation
R/D_V	roll deviation
$N\text{-}S/D_V$	north-south deviation
$E\text{-}W/D_V$	east-west deviation
T_M	time

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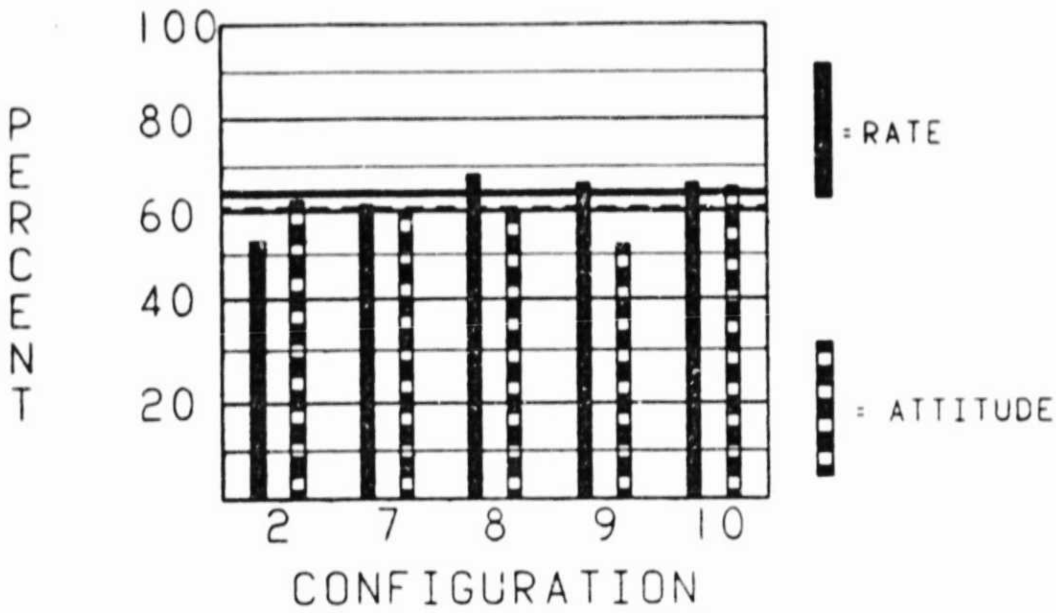


Figure 6-1. Subjective configuration rating.

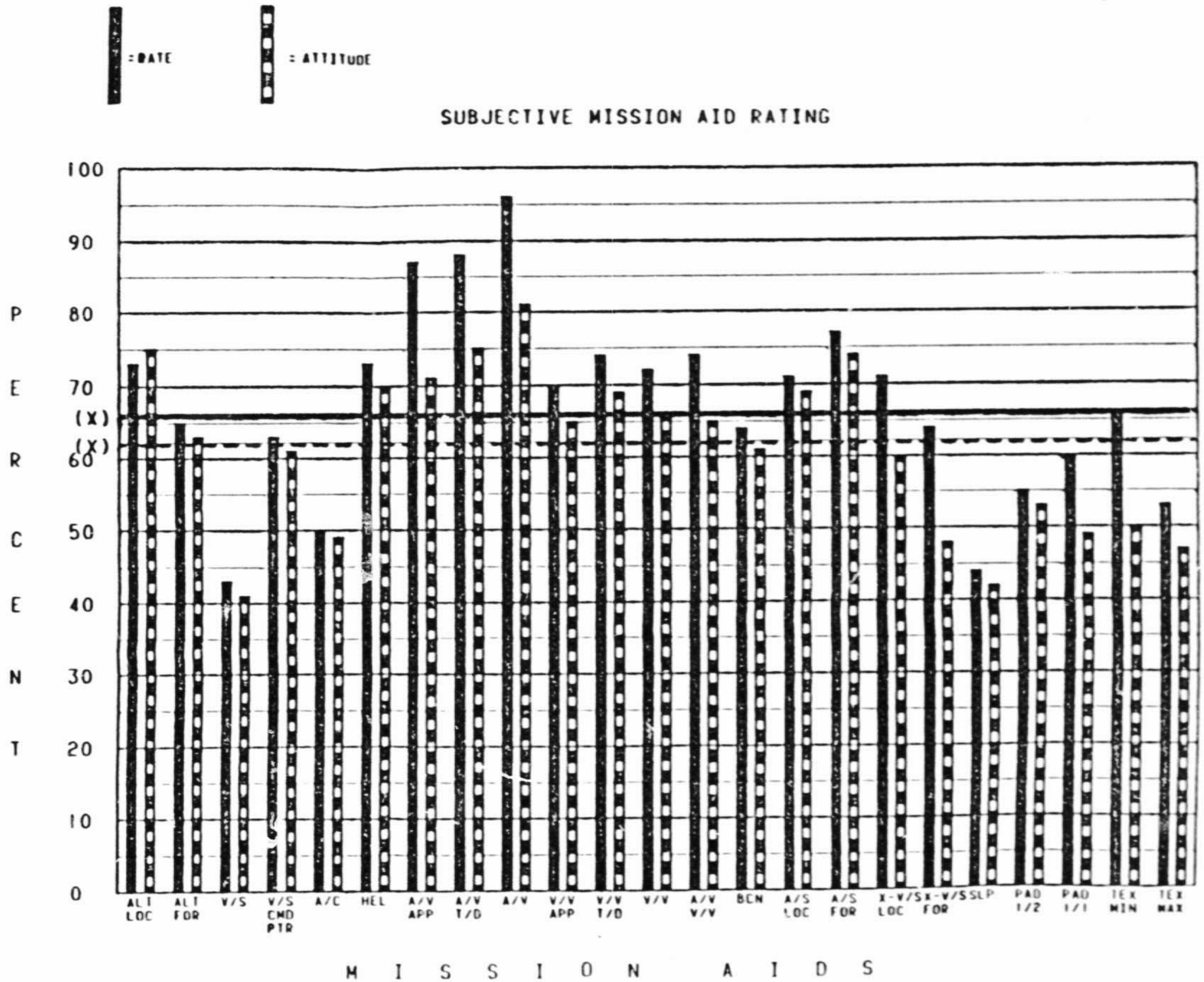


Figure 6-2. Mission-aids ratings.

Parameter	Deviation Values
Vertical touchdown velocity (V_z)	1 ft per sec
Lateral touchdown velocity (V_y)	0.5 ft per sec
Fore/aft touchdown velocity (V_x)	1 ft per sec
N/S deviation from pad center (Y_{Dev})	5 ft from center of pad at touchdown
E/W deviation from pad center (X_{Dev})	5 ft from center of pad at touchdown

This criteria allowed a pass/fail scheme to be assigned in percent for each approach configuration (see Table 6-2). Subjective mission aid rating scale (Figure 6-2) horizontal axis abbreviated symbology is defined as follows:

Abbreviation	Definition
ALT LOC	Location of altitude indicator
ALT FOR	Altitude indicator format
V/S	Vertical speed indicator
V/S CMD PTR	Vertical speed command pointer
A/C	Aircraft symbol
HEL	Helicopter symbol
A/V App	Acceleration velocity - approach
A/V T/D	Acceleration velocity - touchdown

A/V	Acceleration velocity - overall
V/V App	Vertical velocity - approach
V/V T/D	Vertical velocity - touchdown
V/V	Vertical velocity - overall
A/V V/V	Acceleration velocity Vertical velocity overall
BCN	Beacon
A/S LOC	Airspeed indicator - location
A/S FOR	Airspeed indicator - format
X-V/S LOC	Expanded vertical speed - location
X-V/S FOR	Expanded vertical speed - format
SLP	Slip indicator
PAD 1/2	1/2 screen pad
PAD 1/1	Full screen pad
TEX MIN	Minimum texture
TEX MAX	Maximum texture

As can be seen in Table 6-2, configuration #8 received the highest rating in objective flight parameters satisfied.

TABLE 6-2. OBJECTIVE FLIGHT PARAMETERS

Configuration →		2	7	8	9	10	11
Ojbective							
$\bar{x}$ # of flight parameters within established flight criteria in %							
	Attitude	20	80	100	60	60	100
	Rate	20	100	100	80	100	60

7. RESULTS/CONCLUSIONS

Fixed base helicopter simulator experiments were conducted to evaluate a simulated radar presented in pictorial display format. The display was evaluated with 8 variations of added symbology using both rate and attitude command controls. In all cases the subjects were able to make final approaches, decelerate to a hover, and land on a simulated 100 by 100 ft landing pad. Various problems, which are discussed in the following paragraphs were encountered, but the results appear encouraging.

The various display configurations all had the same basic pictorial groundplane, the same symbology to show radar altitude, vertical speed, vertical speed command pointer, glideslope cursor, and an aircraft position cursor. The principal display variations evaluated were those with and without velocity and acceleration vectors, displays with the landing pad shown either one-half or full screen at touchdown, displays with two different degrees of ground texture, and displays with two different vertical speed scales. The makeup of each configuration is listed in Table 5-1. Each configuration was evaluated using both a rate and an attitude control system.

As illustrated in the data analysis (see Section 6), configuration Number 8 received the highest overall ranking when taking into consideration both the objective and subjective ratings of the test pilot subjects. However, because of the small separation of the subjective data results, combined with four configurations (7, 8, 10, and 11) receiving outstanding objective ratings, the data analysis is inconclusive in determining a best configuration. A probable cause for the lack of significant differences in the results is that in the development phase, the concepts that appeared to contribute the least were dropped. Only those combinations that were shown successful in completing the mission were carried into the experimental program.

In the display development phase, it was found that as symbology was added to the display, it quickly became cluttered and hard to interpret. This occurred because the screen was a monochromatic and the picture elements of

the display, as well as the symbols, were developed with computer generated stick figures. In an actual system the radar return would, in most cases, have a recognizable texture and would be a color display so that color separation could be used.

The data show that the rate-command system scored higher than the attitude-command system on all but one each of the subjective and objective evaluations. This high rate command score conflicted with the results reported in Reference 15 where it was shown that an attitude command control system was superior. However, close examination of the stick motion plots revealed that the pilots were usually not flying the rate system in the critical slow speed and hover part of the task. The flight control system had a "beep" trim available in both the rate-command and attitude-command modes, which was explained in Section 4. The "hat" switch on top of the cyclic stick, which was controlled by thumb motion, could be used to command a new attitude. At slow speeds and hover, all of the pilots used little stick motion and commanded attitude with the trim switch; a rather dramatic indication that they preferred that method of cyclic input. The "beep" command input actually had about twice the sensitivity compared to that used in the attitude-command mode. This may be a reason for better accuracy in hover with this mode of operation as compared to the attitude command mode. In addition, there was a stick motion threshold resulting from the fact that when rate is being commanded, a zero command signal must be maintained by using a threshold in the stick motion sensing scheme, otherwise, drift will result.

Holding the stick motionless and using the high sensitivity "beep" attitude command seemed to be the preferred and most accurate cyclic control when hovering.

These results positively conform with past evidence that attitude command controls are preferred. A rate-command control system will probably not provide adequate control for the hover task for the following reasons:

a. The pilot is required to continuously control attitude, rather than command it.

b. The task of continuous adjustment for control adds too much additional workload.

c. To control attitude by rate command, the pilot spends too much time scanning the attitude display.

However, it is possible that a large wide angle display with a true perspective image might produce adequate attitude information so that a rate-command system would be feasible.

The pictorial display permitted the test pilot subjects to judge relative helicopter position with respect to the glideslope and landing pad so that they were able to proceed to touchdown in all cases. However, the precision of altitude and translational control was poor in many cases. Altitude was an obvious perceptual problem because it was difficult to show a normally wide angle landing scene on a narrow view CRT, as discussed in Section 4. This problem requires further study. The scale change algorithm may be improved or the scale change might be stopped at some predetermined altitude with further descent cues shown on a vertical scale such as the one used in this experiment. We know from this study that the combination of expanding scale image and the vertical scale were used to make successful landings but that pilot workload was deemed to be too high by the subject pilots.

Control of horizontal translation was also good enough to land but was erratic and required excessive pilot control effort. Two other problems were identified: excessive lag in the display update time and its interrelationship with the altitude display. The visual lag in the displayed information was caused by the slow update capability of the graphics generator. With the information displayed, its update delay was 400 milliseconds. This delay, combined with the stick threshold previously mentioned, caused a tendency to

over-control. By adding velocity and acceleration vectors, the x and y translation was easily controllable; without the vectors considerable pilot-induced oscillation and a high workload existed.

The use of the expanding scale radar display caused translation rates to appear to be the same on the display as in the real world. Thus, if the scaling is incorrect, the translational velocity will also appear incorrectly. Correction of the altitude scaling should also correct translational velocity cues. The solution for improved velocity cues is the reduction of display update lag time (by means of an improved graphics display generator) and corrected altitude scaling. By these means it may be possible to dispense with the velocity and acceleration cues. This study has shown that even with the display deficiencies, the velocity and acceleration vectors enabled hooded touchdown using only the instrument display. Heading hold was used in this study to reduce the work of controlling that channel.

In summary, the results of this experiment add weight to the conclusion that imaging systems and displays allow the use of situation information to provide the pilot with adequate cues to the extent that he can formulate his own commands. Prior work which resulted in contradictory conclusions did not use pictorial imaging systems and was, therefore, driven to provide quickened, command-indicating displays using the pilot as a command-follower.

A continuation of this effort, in a moving base NASA simulator, using refined displays and controls, has promise of solving many of the problems of zero visibility IFR flight in VTOL aircraft.

8. RECOMMENDATIONS

After reviewing all the data, conclusions, and subjective comments from the pilots who participated in this project, the following recommendations are made for the follow-on evaluation in the NASA moving based simulator:

System Improvements

a. Increase the display update rate to as near real time as possible, e.g., 10 updates per second or more, to avoid lags in the pilot's perception of change.

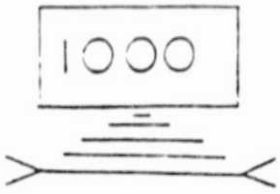
b. Incorporate a heading hold system which allows yaw-trim corrections to be accomplished using the tail rotor pedals when not in hovering flight.

c. Use lateral acceleration measurement indicated by the inclinometer as a slip indication.

Display Improvements

a. Results of the experiment and pilot comments indicate considerable confusion with the scaling and motion of the altitude, vertical speed, and vertical speed command symbols. In addition, interference with these readouts resulted from landing pad being superimposed on the display. The symbol shown in Figure 8-1 was designed to resolve these problems, and it is suggested that this symbology be evaluated in the next phase.

The altitude is presented in a sensitized digital readout. Vertical speed is indicated by the growing pyramid and command vertical speed is indicated by the moving indices which show ascent above and descent below the altitude number.



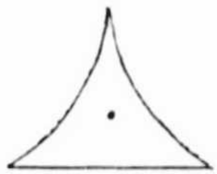
1. Sensitized digital readout.
2. IVSI lines assigned a value for each line.
3. Ideal descent rate pointers would move above rad. alt. for missed-approach climb indication.

Figure 8-1. Sensitized digital readout.

b. Several pilots also requested a single aircraft symbol that would show landing position with more precision. The position symbol shown in Figure 8-2 is recommended for the next test phase. The position symbol design is intended to make the touchdown area more visible, and the curved exterior lines will prevent confusion with other symbols.

c. Results of the experiment and pilot comments indicate the need for further investigation of the requirement for velocity and acceleration vector symbols sensitivity.

d. Incorporate a symbol in conjunction with the airspeed scale that would designate the ideal airspeed for the approach angle selected and the closure rate.



1. ID of symbol should be large enough to fit the beacon inside at touch down.

2. Symbol should be brighter than adjacent symbols.

Figure 8-2. Aircraft position symbol.

e. Investigate the landing pad algorithm and scaling to determine the most realistic image. Consider the inclusion of perspective and a fixed scale when near touchdown.

f. Use color to aid in discrimination between symbols.

g. Consider presenting critical information on a head mounted display to provide the pilot with the capability of using visual contact cues as soon as they become available.

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APPENDIX A

TEST PLAN/DATA ANALYSIS PLAN

FOR

INVESTIGATION OF IMAGING AND FLIGHT

GUIDANCE CONCEPTS FOR ROTORCRAFT

ZERO VISIBILITY APPROACH AND LANDING

Bell Helicopter Textron Inc.
Report 699-099-065
Contract NAS2-11364
Revised 7-28-83

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1. SCOPE

The objective of this study is to examine the ability of helicopter pilots in a simulated environnment to utilize a simulated imaging display to accomplish landing approaches, hover, and touchdown. The incorporation of symbology on the imaging display will be examined to determine improvement in pilot performance as a function of added symbology. The degree of artificial stability and control will be varied. A matrix of test conditions has been established and will be used to define the combinations to be examined. Test subjects will fly the simulati ¬ and provide subjective data using questionnaires as defined herein.

2. SIMULATION ENVIRONMENT

An earlier task was to develop a simulated environment that permited examination of the displays in question. This task included a suitable set of equations of motion and a suitable cockpit with appropriate displays, including a simulated radar and establishing the detail configurations of the symbology elements to be used in the test matrix. These details were established by subjectively evaluating various display elements in a preliminary set of tests involving HFE and qualified helicopter pilots. Changes in symbology or the addition of elements was accomplished until a set of configurations was established. These configurations consist of a baseline system of standard instruments and a simulated radar, plus others with increased enhancement by symbology elements.

The control laws were modified to provide minimum adequate artificial stability to allow mission performance with a given display configuration. Emphasis was placed on the slow speed (below 40 KIAS) flight regime.

The maneuvers include the steady-state approach, the deceleration to a hover, the steady-state hover, and touchdown.

The overall experimental task will be to determine the best set of symbology and control laws to be used with the simulated radar imaging display to permit the pilot to perform IFR approach maneuvers.

The pilot subjects will be brought into the simulation on a formal basis. The mission to be examined during this study will include the helicopter IFR approach from approximately 1000 feet A.G.L. to touchdown. This will include a comparison between the pilot flying the approach maneuvers with and without attitude reference data being presented on the micro-HUD. The basic simulated radar image display (SRID) with selected symbology will be used and the single variable will be the micro-HUD. Presentations will be balanced.

3. SIMULATION EQUIPMENT

3.1 SIMULATION SYSTEM

The Bell simulation facilities to be used are in the BHT Interactive Simulation Lab. Figure 1 illustrates the overall laboratory equipment and interconnection. The cockpit utilized for zero visibility simulation is fitted with the CRT displays, micro-HUD, standard instruments, and controls needed for these tests. Overall operation is under control of the Simulation Executive System (SES) developed by Bell. Figure 2 illustrates the functional relationship and information flow in the system. The SES provides programs to store, process, and plot data in tabular and graphic form. The AD10 parallel processor provides a portion of real-time processing of the control-law implementation of SCAS and AFCS functions, while the VAX processes the equations of motion and graphic output. The helicopter mathematical model will be run under the ARMCOP program, which is installed in the Bell SES. Figure 3 is a photo of the simulation cockpit to be used for these tests. Figure 4 is a view showing the cockpit panel and CRT. Figure 5 illustrates the micro-HUD eyeglass display.

3.2 COCKPIT EQUIPMENT

The cockpit instrument panel is arranged as shown in Figure 6. A set of standard flight instruments are present in addition to the CRT display. An auxiliary CRT provides display of modes.

No engine instruments (temperature, N1, N2, etc.) are provided, since it is assumed that a governor is managing throttle activity.

A standard cyclic stick and pedal arrangement is provided. The cyclic grip contains radio/ICS, FORCE-TRIM, release ATTITUDE-TRIM, AFCS DIS, and CARGO REL switches. The collective stick is a standard stick with friction, except the head is a wooden mockup that has switches for controlling the mode of operation and beacon location.

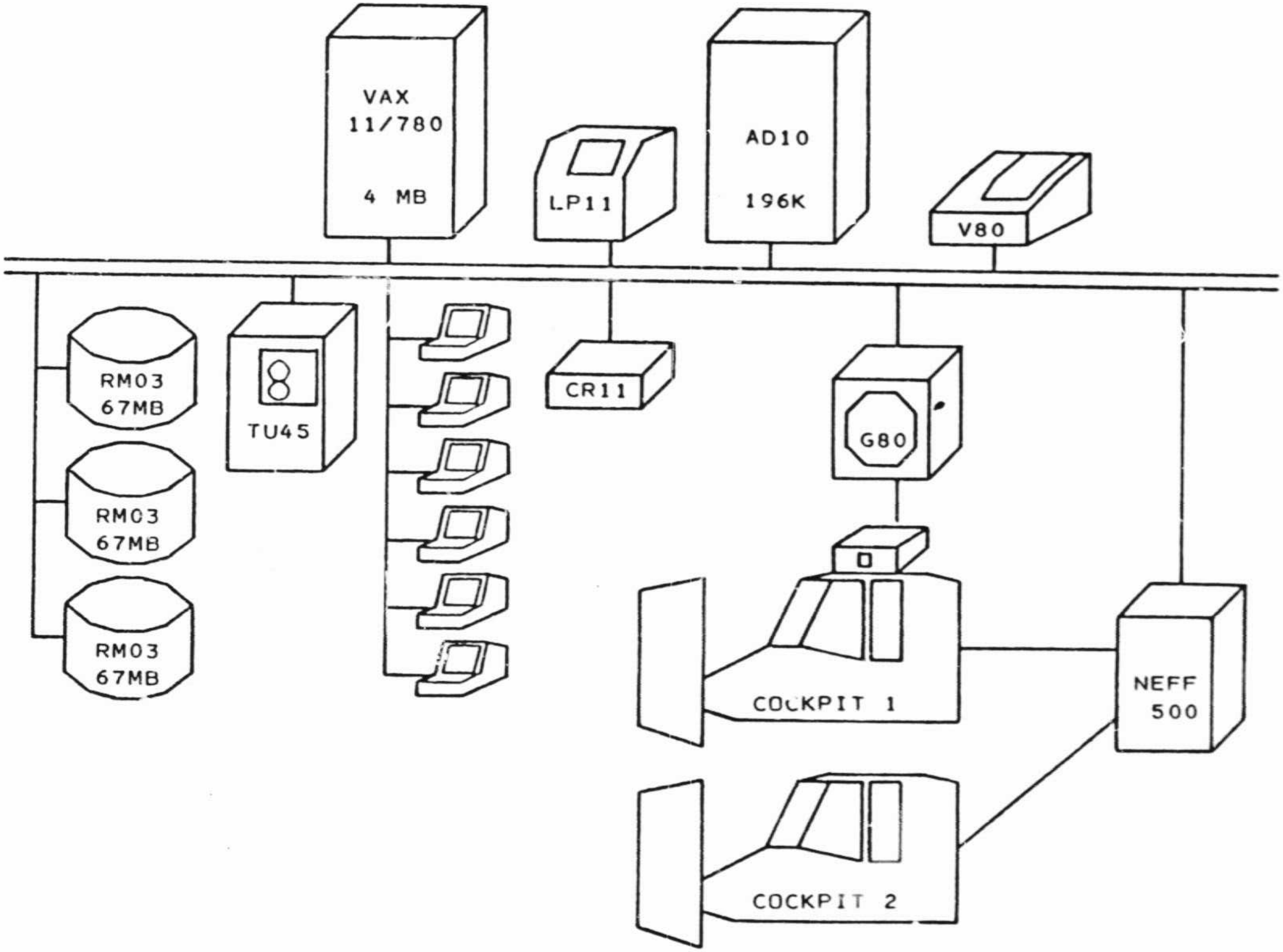

Figure 1. Bell Interactive Simulation Lab.

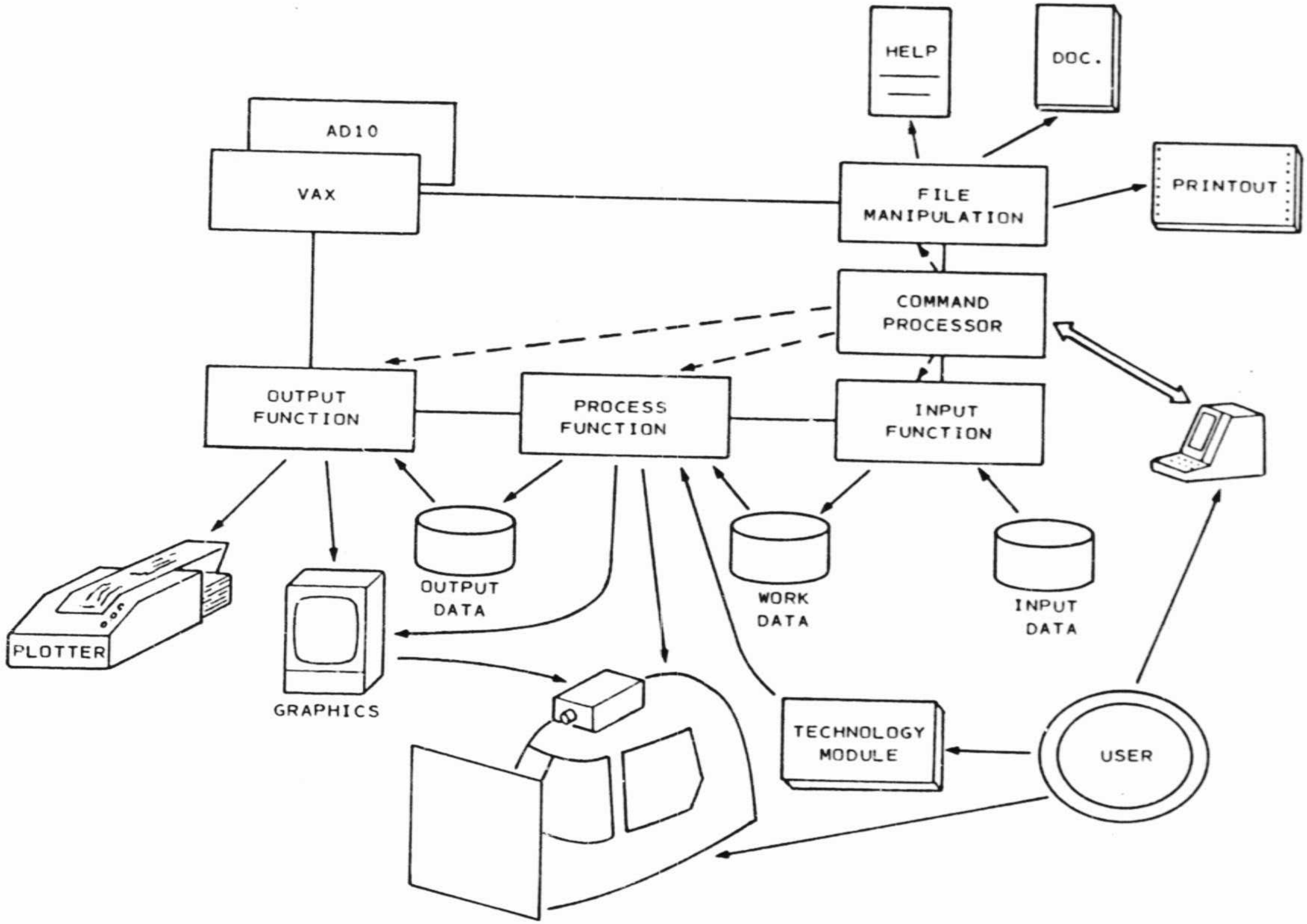

Figure 2. Simulation Executive System.

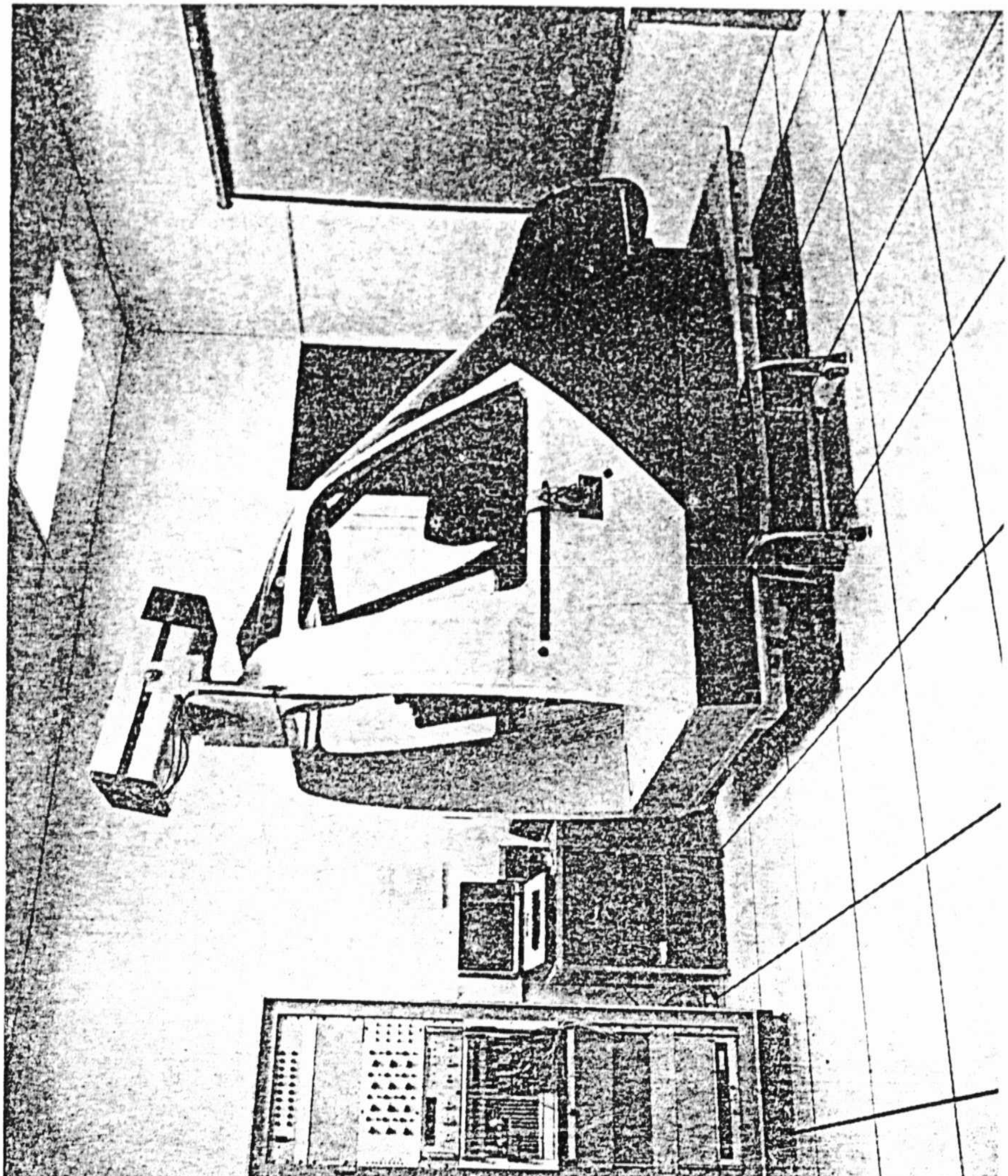

Figure 3. Simulation Cockpit.

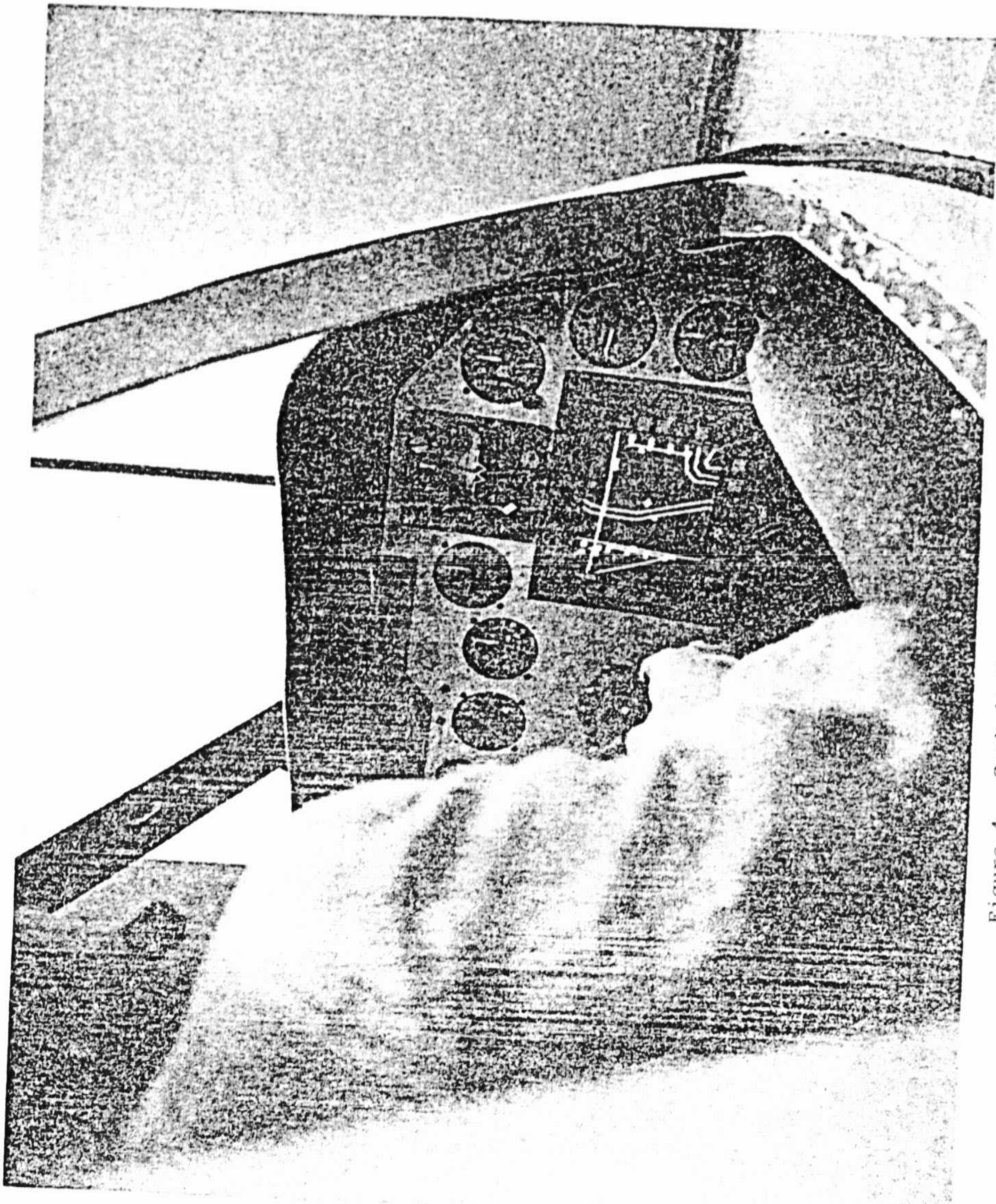

Figure 4. Cockpit Panel and CRT.

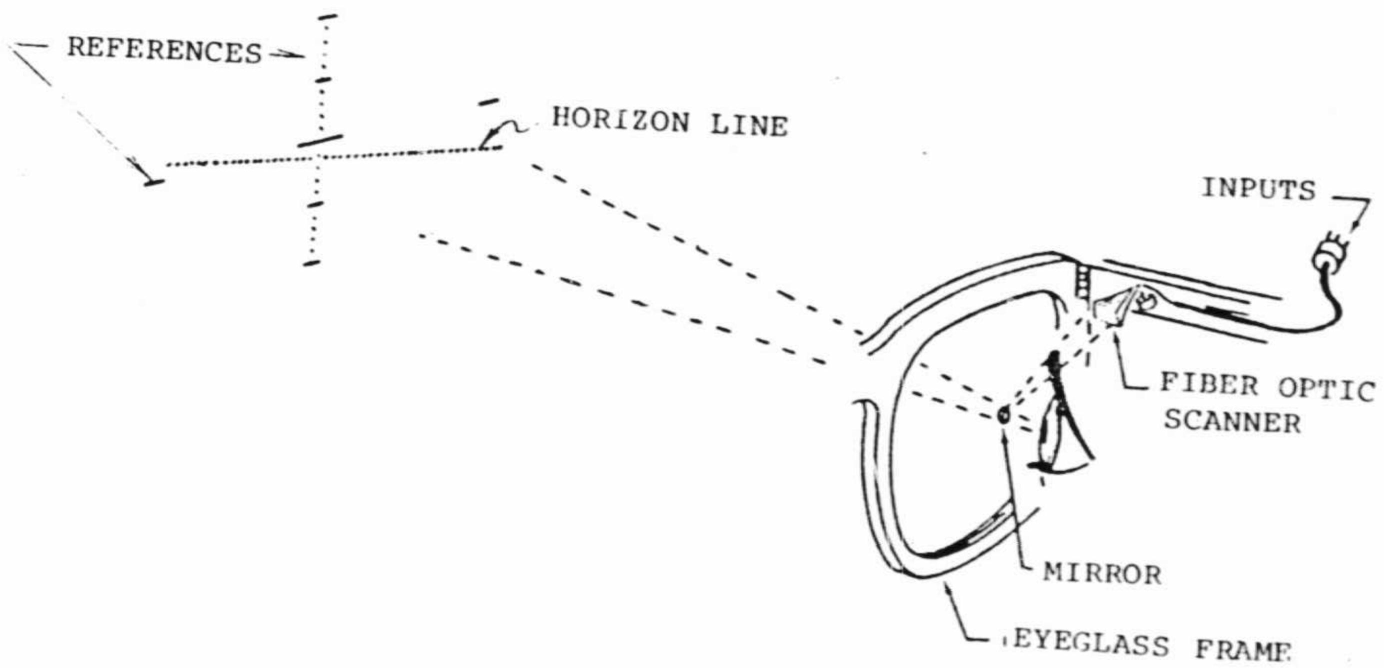

Figure 5. Micro-HUD Display.

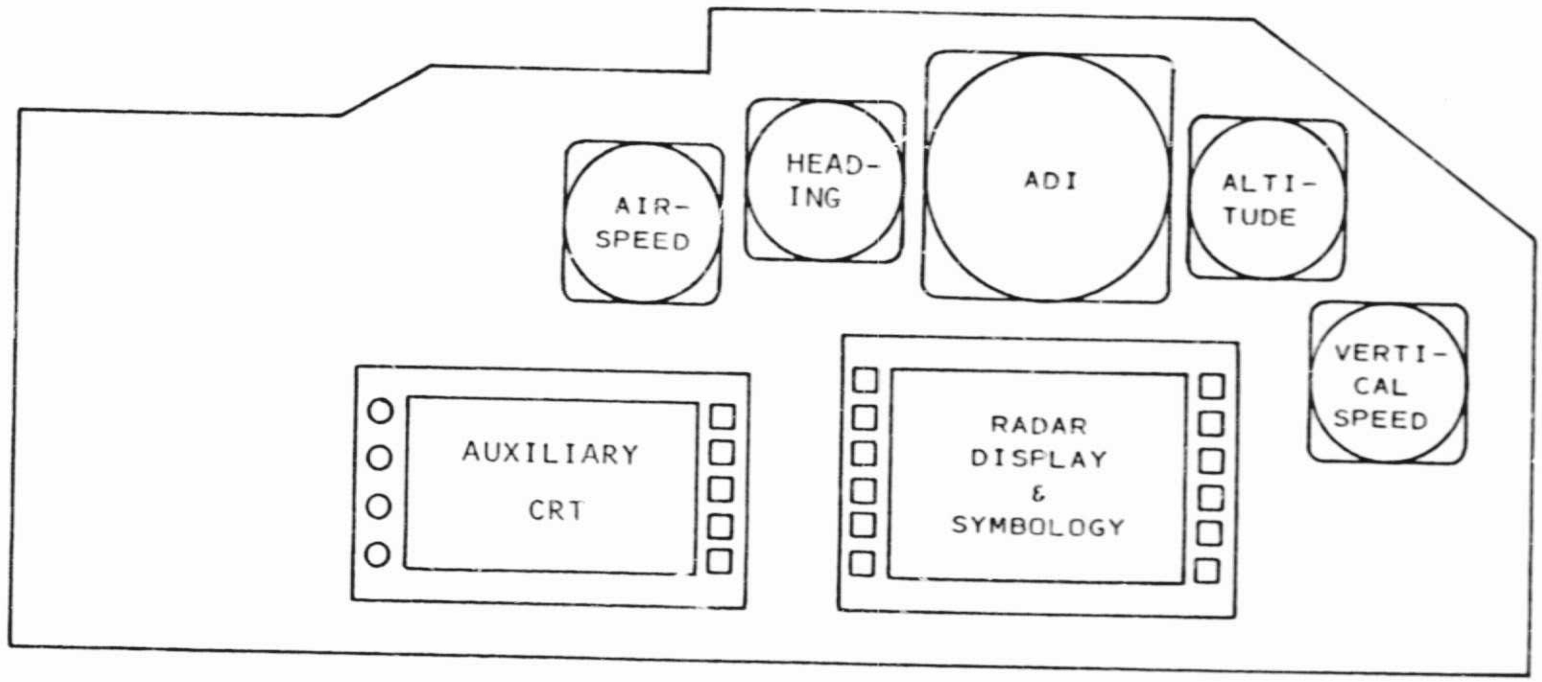

Figure 6. Cockpit Instrument Panel.

An electrohydraulic actuation system is tied to the cyclic stick and pedals. An electronic control system emulates force-trim, and attitude-trim characteristics.

The micro-HUD display generation system is mounted in the nose compartment of the cockpit. Connectors for the display unit are conveniently located in the cockpit.

A Vector Automation Graphicus-80 (G80) graphics generation system is used to generate images on the instrument panel CRT.

A high-resolution radar image has been simulated by means of computer graphics using the G80. The display has been incorporated in the simulator, described above, and will respond to pilot-in-the-loop commands to simulate the radar display during a complete flight. The tests will concentrate on the approach and landing part of the mission.

The simulated radar display has been augmented to add symbols to aid in precision control of the approach.

Conventional instruments, including an ADI, are mounted in the instrument panel adjacent to the radar display to provide additional information to the pilot.

3.3 CONTROL SYSTEM DESCRIPTION

Equipment - The equipment for the cockpit used in this test program, consists of hardware external to the cockpit and specialized cockpit equipment. The cockpit equipment includes the following items:

3.3.1 Cyclic Control Stick

The cockpit includes a cyclic stick of standard type. The stick has a four-way beep switch for control system trim, a trim release switch for referencing

the stick and other switches not used for these tests. The stick operates against two electrohydraulic actuators, one for fore-and-aft and one for lateral motion. Two sets of position sensors measure stick motion. One set transmits signals to the computer input interface (NEFF). The other set is used within the cockpit to control stick forces and positions. A set of strain gauges on the stick measure force as applied by the electrohydraulic actuators. An analog electronic control unit within the cockpit provides control of the electrohydraulic servo valves on the actuators. The analog system is designed to emulate the force-trim system of the Bell Models 222, 412 and others. Using the position sensors and strain gauge signals, the stick is made to present a force gradient with a breakout force. The beep and trim release connections are also made to emulate their normal operation in a helicopter. The beep and trim-release functions are also interfaced as discrete logic inputs to the computer system.

The cyclic stick also includes a standard mechanical friction device which can be adjusted by the pilot.

An external hydraulic power unit supplies the cyclic stick actuators. A force-trim on-off switch is located on the center console.

3.3.2 Collective Stick

The cockpit includes a standard type collective stick. The stick has a mechanical adjustable friction device to maintain its position. The head contains a switch for changing the flight display mode and other switches not used for these tests. A position sensor is connected to the computer interface unit (NEFF).

3.3.3 Pedals

A set of standard pedals is included. A motion transducer feeds pedal position to the computer. A mechanical spring centering arrangement returns the pedals to a fixed position when they are released.

3.3.4 Computational Equipment

The control system uses both the AD10 and VAX computers. The AD10 is used for the faster real-time computations, while the VAX executes the slower ones. The VAX also executes the helicopter dynamic model and the overall operating system.

The cockpit contains pushbutton switches which communicate with the computer for control of simulation modes and to provide computer reset. Also, indicators are provided for use in setting the pilot's controls to their trim positions for startup.

3.4 CONTROL SYSTEM OPERATION

The control system provides augmented flight control for pitch, roll, yaw and collective control. There are two modes of control to be used in this test program, relative to pitch and roll attitude control. One mode provides direct attitude command with attitude hold. It is termed the ATTITUDE command mode. The other mode provides attitude hold, but has a rate response to pilot input. It is termed the RATE command mode. The yaw axis uses a single mode which is a heading hold mode. The vertical axis provides a slightly reduced velocity response.

3.5 PITCH/ROLL ATTITUDE HOLD

Both the ATTITUDE and RATE command modes use straightforward attitude and rate feedback terms. The two modes differ in the means for pilot commanded changes to the reference attitude. In the ATTITUDE mode the reference attitude is fixed to the value for the initial flight condition of the aircraft. The reference may be beeped from that point. Motion of the stick from the reference point causes the aircraft to assume a new attitude with a steady-state value proportional to stick displacement. The long term attitude response is reduced by aircraft velocities causing buildup of attitude error. The short-term response is of greater magnitude, since the aircraft translational veloc-

C-2

ities stabilize over a much longer period. A degree of initial response quickening is provided in the control system. A washout network provides the function as shown in Figure 7. The stick position is fed to the network and summed with the rate feedback signal. Figure 7 also shows the provisions for referencing and trimming attitude.

In the RATE command mode provisions are made to sense pilot effort in moving the stick from a reference position. The position reference is held at an integrator output and is re-referenced any time the pilot re-references the stick by beeping, or pressing the TRIM REL switch on the cyclic stick. Moving the stick from the reference point generates a signal which, after passing through a threshold, drives the integrator, causing constant retrimming of attitude as long as the pilot maintains stick displacement. The displacement determines the attitude rate resulting from a given stick motion.

The mode change switch is a software flag set before each simulation run cycle.

3.6 HEADING AXIS

The heading axis control system provides heading hold at all times. The pedals are used only to change heading and are not needed to compensate for large power changes

Figure 8 illustrates the yaw axis control system block diagram. The heading reference is first slaved to the initial heading where the simulation begins. An integrator holds the reference heading when the simulation is run. Changes to the reference heading can be made by displacing the pedals from the spring centered position by more than a threshold amount (0.5 inch). The yaw rate is proportional to the displacement beyond the threshold. An integrator takes any heading error and provides a steady state value of tail rotor pitch adequate to zero the error. This allows maintenance of heading regardless of the large power change encountered during the approach and transition to hover.

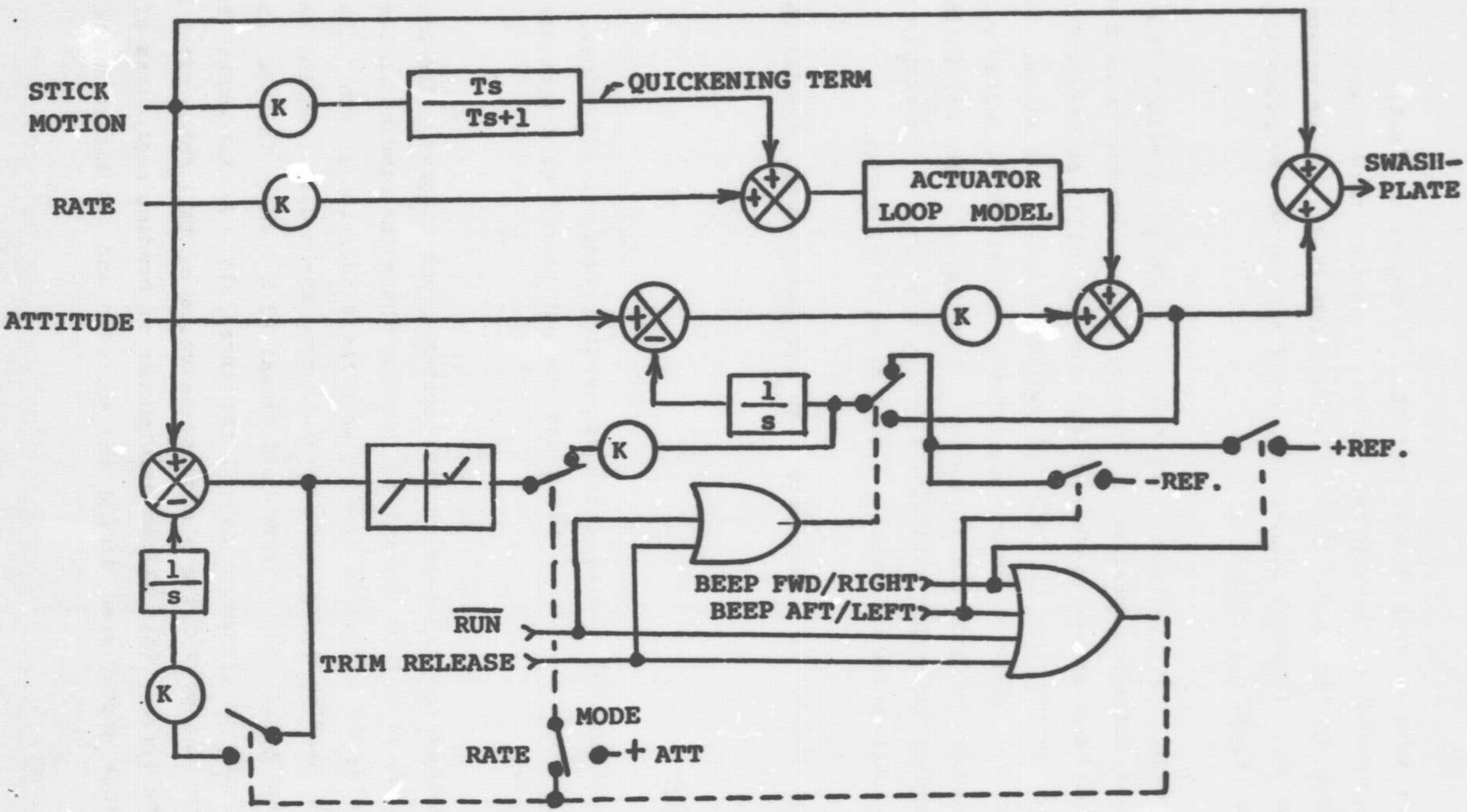

Figure 7. Block Diagram - Pitch/Roll Controls.

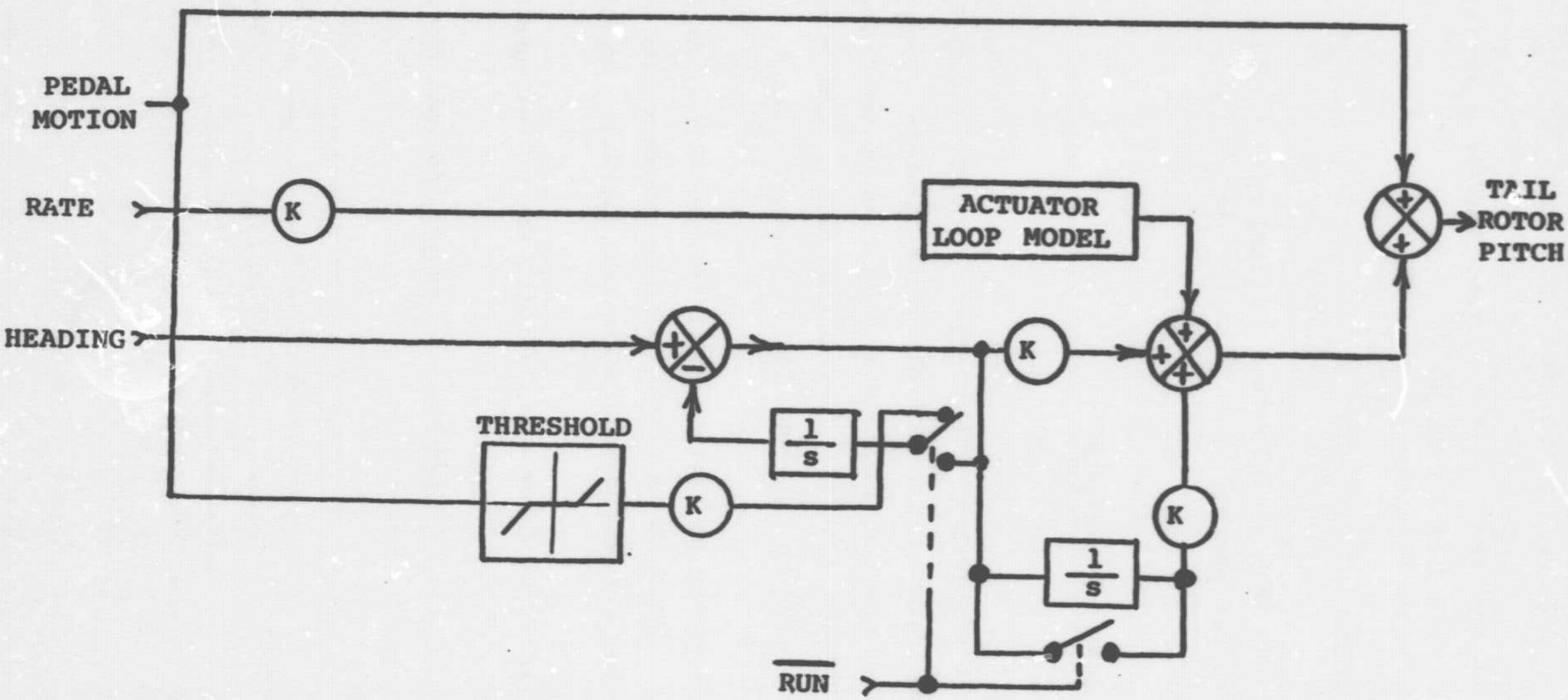

Figure 8. Block Diagram - Heading/Yaw Control.

The pedals are not moved by the system, therefore is is assumed the cross coupling is removed from the flight controls.

3.7 VERTICAL AXIS

The vertical axis is provided with a vertical rate feedback term with very low gain (0.001 radian per foot per second). This damping is always in effect while running.

3.8 CONTROL SYSTEM PARAMETERS

The gains, time constants and initial conditions are contained almost entirely in the digital simulation. The computer program listings shall be made to record values. Some of the control system parameters are set by adjustments on and within the analog force-trim simulation system. The parameters shall be set and checked initially and periodically, once a week. A 20 minute warmup period shall be allowed for the analog system to reach stability.

The force-trim system parameters shall be maintained constant throughout the test program. Measurements shall be made to determine the values of the following control system parameters with the hydraulic supply set at 1000 psi.

1. Cyclic stick force-trim breakout force. Measure with spring scale.

	Measured	Desired Nominal Value	
Right	________	____________	lbs.
Left	________	____________	lbs.
Foreward	________	____________	lbs.
Aft	________	____________	lbs.

2. Cyclic stick force gradient. Using scale and spring scale measure force for a 5-inch displacement from the trim position. For each direction subtract the breakout force and determine the gradient.

	(Pounds - Breakout) ÷ 5		Desired
Right	____________	lbs. per inch	____________
Left	____________	lbs. per inch	____________
Foreward	____________	lbs. per inch	____________
Aft	____________	lbs. per inch	____________

3. Cyclic stick breakout force - with force-trim turned off measure the static breakout force in all four directions.

	Measured	Desired	
Right	________	____________	lbs.
Left	________	____________	lbs.
Foreward	________	____________	lbs.
Aft	________	____________	lbs.

4. TESTS TO BE PERFORMED

4.1 EXPERIMENTAL DESIGN

Eleven display configurations and two control systems will be compared by the pilot subjects. It is planned that the order of presentation of the two control systems will be balanced and the eleven display configurations will be randomized to minimize learning and fatigue effects.

The following pages contain illustrations and descriptions of the various symbols, on an individual basis.

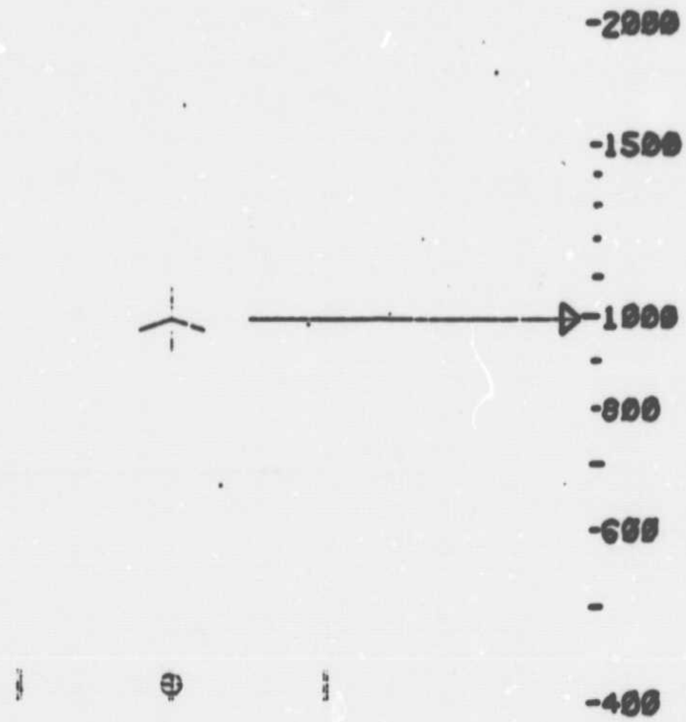

Figure 9. Radar Altitude Scale.

4.1.1 Symbol Description

Radar Altitude Scale: Radar altitude is presented on the right side of the CRT using a rolling, nonlinear scale with a fixed pointer. The upper limit of the scale is 2000 feet and the lower limit is 0. The nonlinear scale is defined as follows:

- 0-5 feet in 1 foot increments
- 5-20 feet in 5 foot increments
- 20-100 feet in 10 foot increments
- 100-200 feet in 50 foot increments
- 200-1500 feet in 100 foot increments
- 1500-2000 feet in a 500 foot increments

If altitude increases above 2000 feet A.G.L. the radar altitude scale is blanked from the screen. Radar altitude is available in all configurations and all modes of flight i.e. cruise, entry, approach, transition, hover.

Figure 10.

<u>Vertical Speed Scale</u>: Vertical speed is indicated by a horizontal line drawn on the right side of the CRT immediately to the left of the radar altitude scale. The only numeric indication of vertical speed is equal to 0 rate of climb. The vertical speed indication is directional and linear in movement. When the line is adjacent the triangle on the the radar altitude scale the aircraft is neither climbing nor descending. Vertical speed indications are available in all configurations when the approach or transition mode is selected.

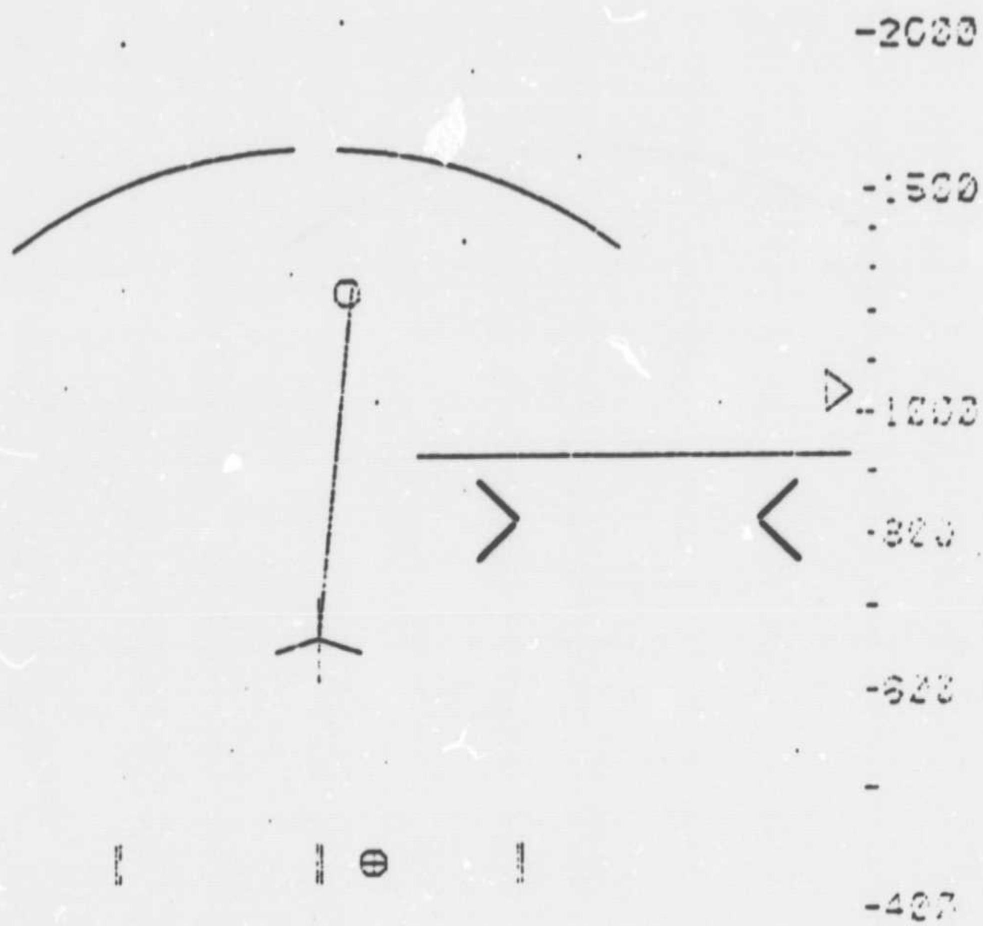

Figure 11.

Vertical Speed Command Pointer: The command pointers work in conjunction with the vertical speed indicator. They are a fixed set of pointers located to the left of the radar altitude scale. When the vertical speed line is centered on the pointers and the glideslope cursor is over the intended touchdown point the proper rate of descent has been established for the selected approach angle. The vertical speed command pointers are available in the approach and transition modes.

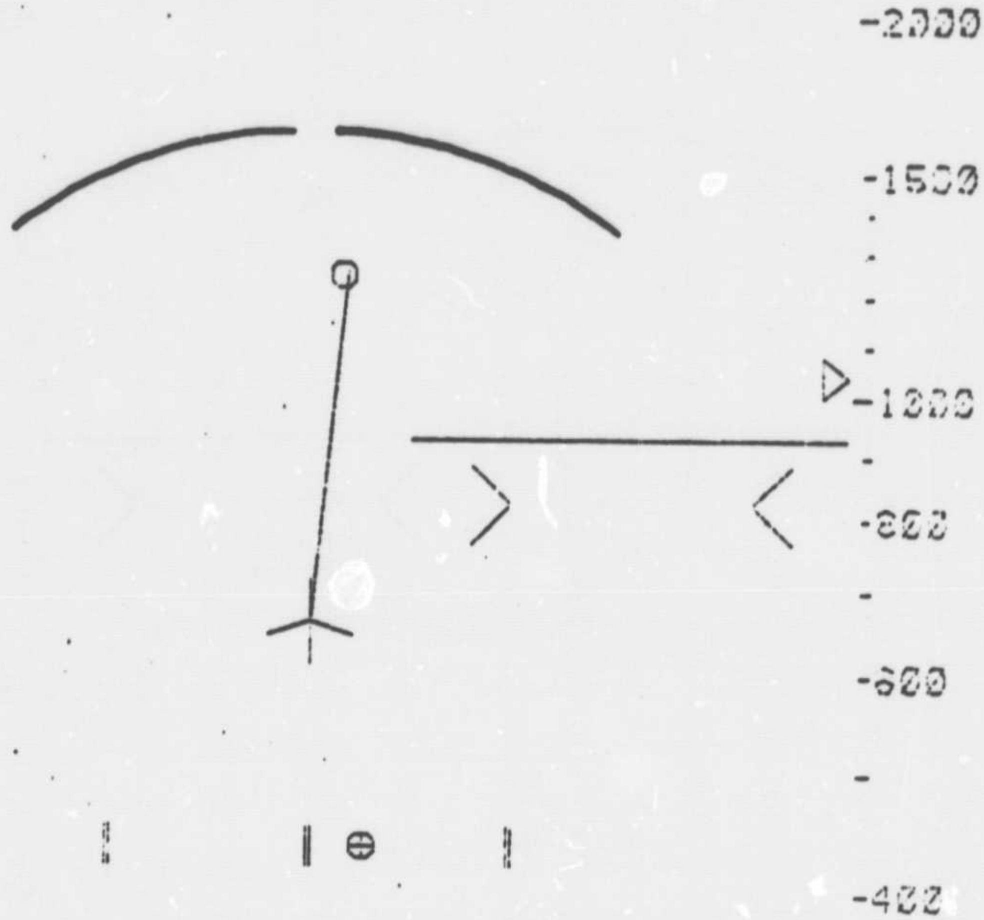

Figure 12.

Glideslope Cursor: The glideslope cursor is a fixture that is located slightly above the center of the CRT. When the center of the cursor is placed over the intended touchdown point the proper approach angle has been intercepted. The cursor is available in all configurations when either the approach or transition mode is selected.

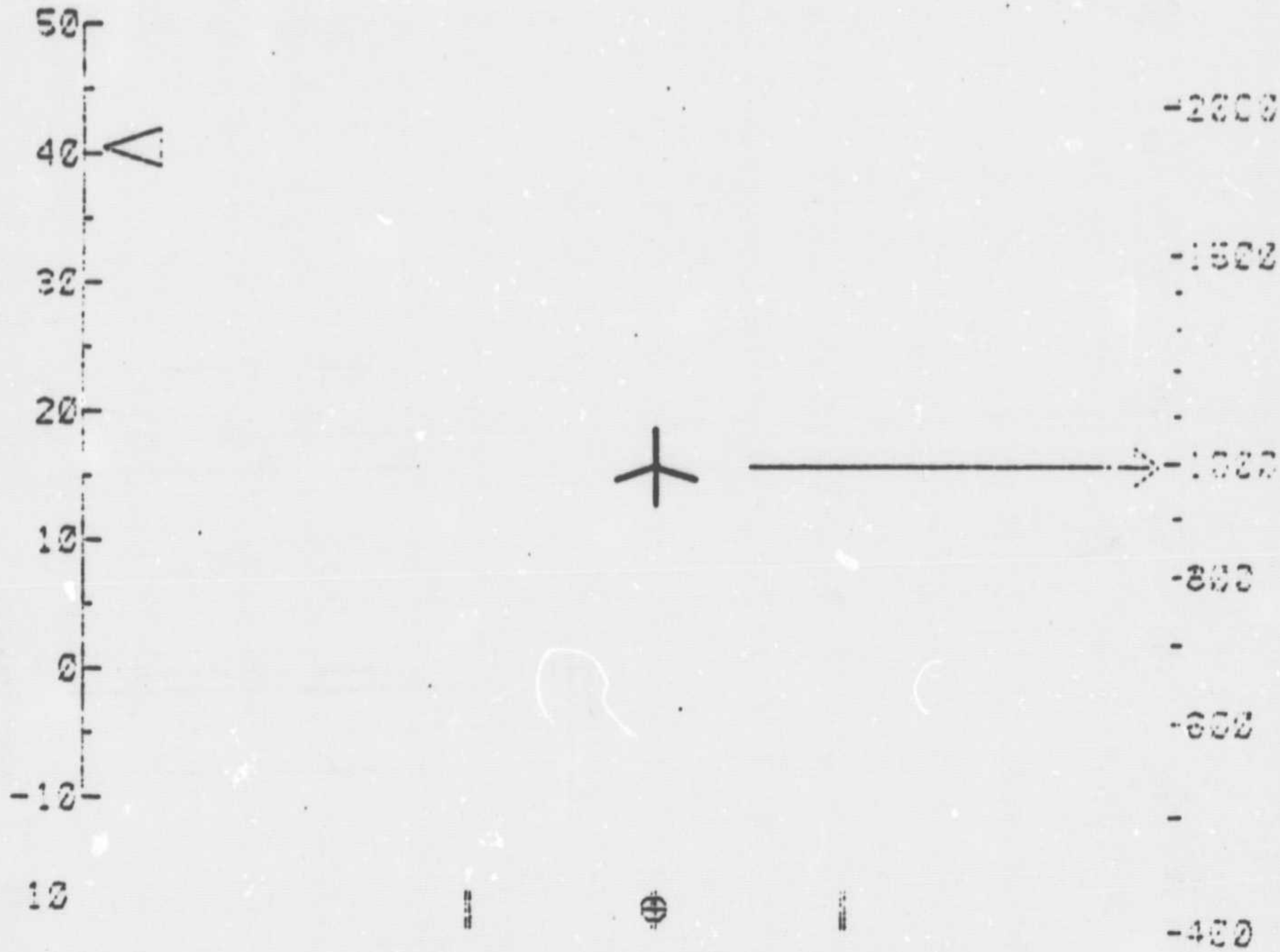

Figure 13.

<u>Aircraft Position Cursor</u>: A fixed index located in the center of the lower 1/3 of the CRT is used to designate the location of the aircraft. The aircraft position cursor is available in all configurations and modes with the exception being no position cursor is presented when the helicopter symbol is present.

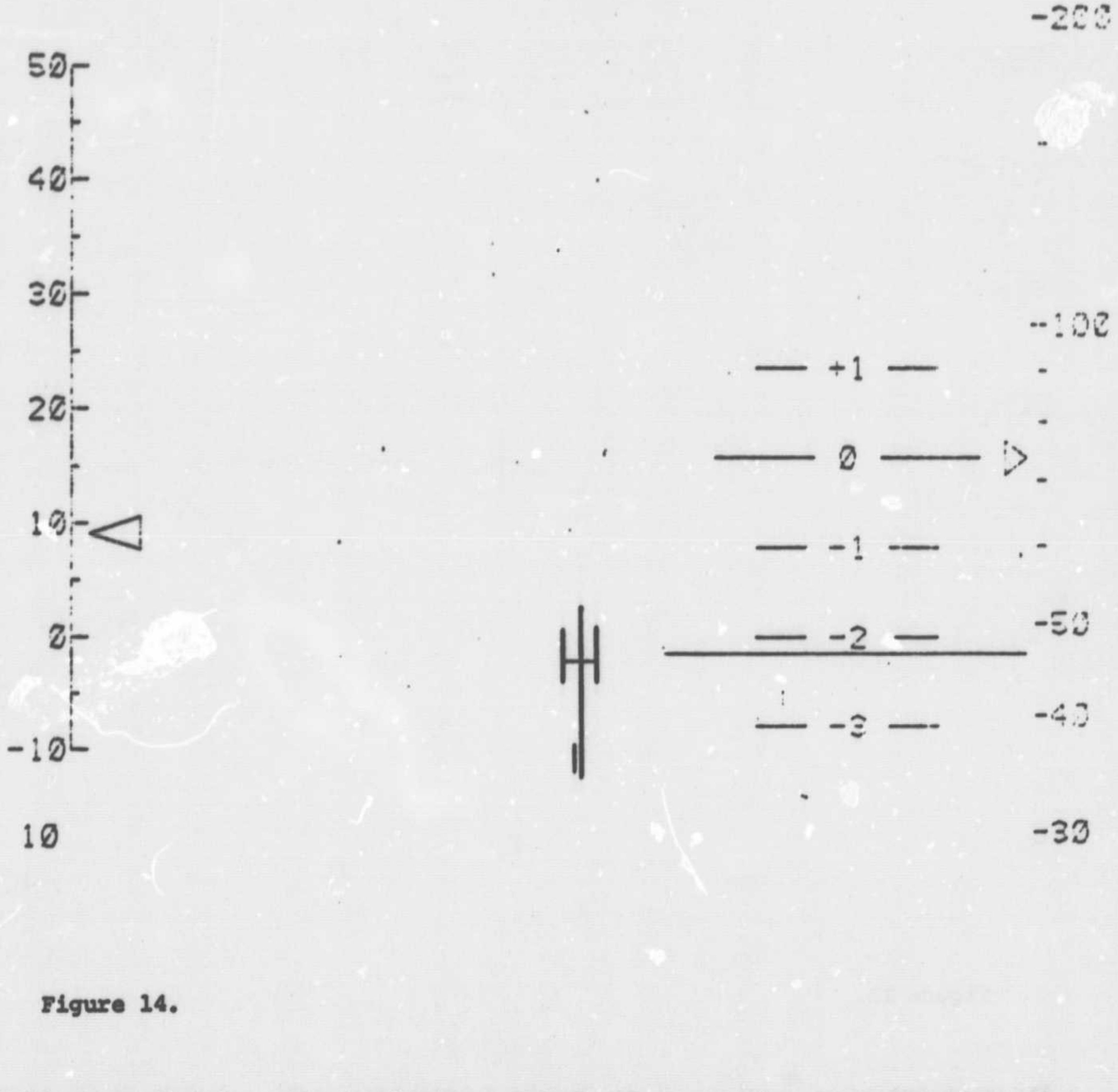

Figure 14.

<u>Helicopter Symbol</u>: The helicopter symbol is a graphic representation of a helicopter located in the center of the lower 1/3 of the CRT. This symbol is only available during specified configurations and then only in the transition and hover modes. It is used to designate the position of the helicopter over the ground.

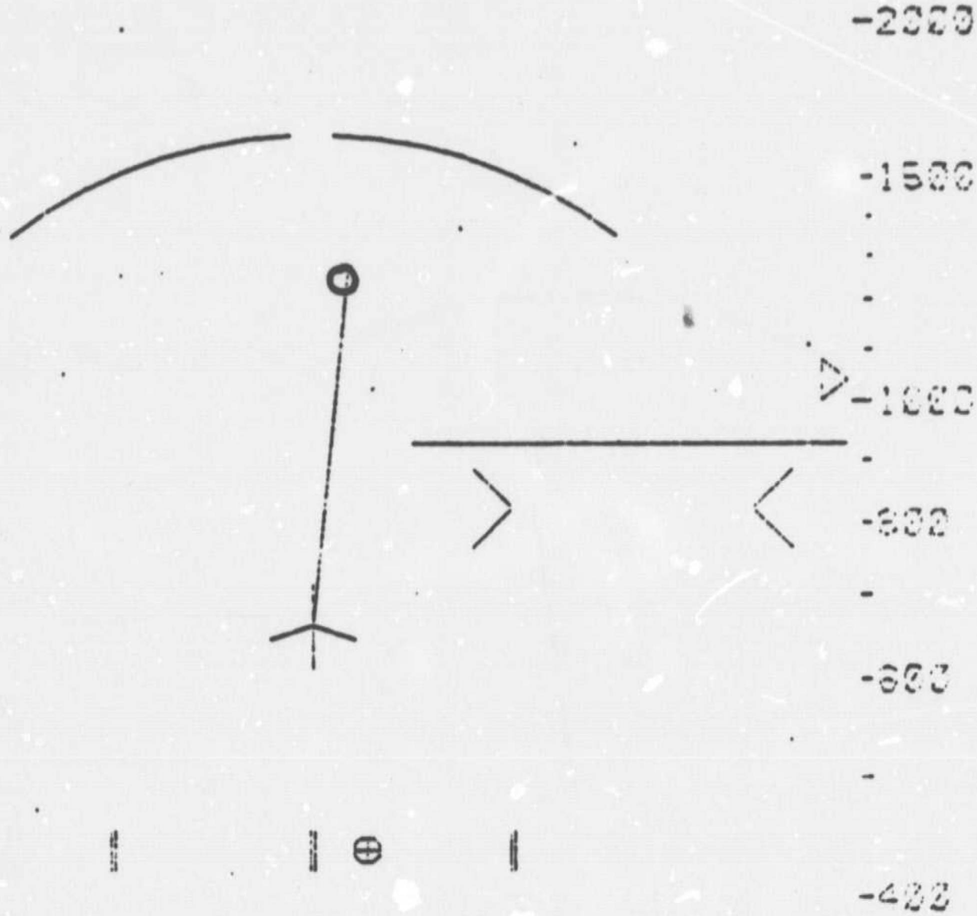

Figure 15.

Acceleration Vector: The acceleration vector is depicted as a circle that moves from the tip of the velocity vector symbol in the direction the helicopter is accelerating. The acceleration vector and velocity vector work in conjunction with each other to indicate acceleration, speed and direction of movement of the helicopter. When the acceleration vector circle is coincident with the velocity vector tip, no acceleration or deceleration is taking place. If the velocity vector and the acceleration vector are centered on the aircraft position cursor/helicopter symbol, the helicopter is at a stable hover. The acceleration vector is available in specified configurations and modes.

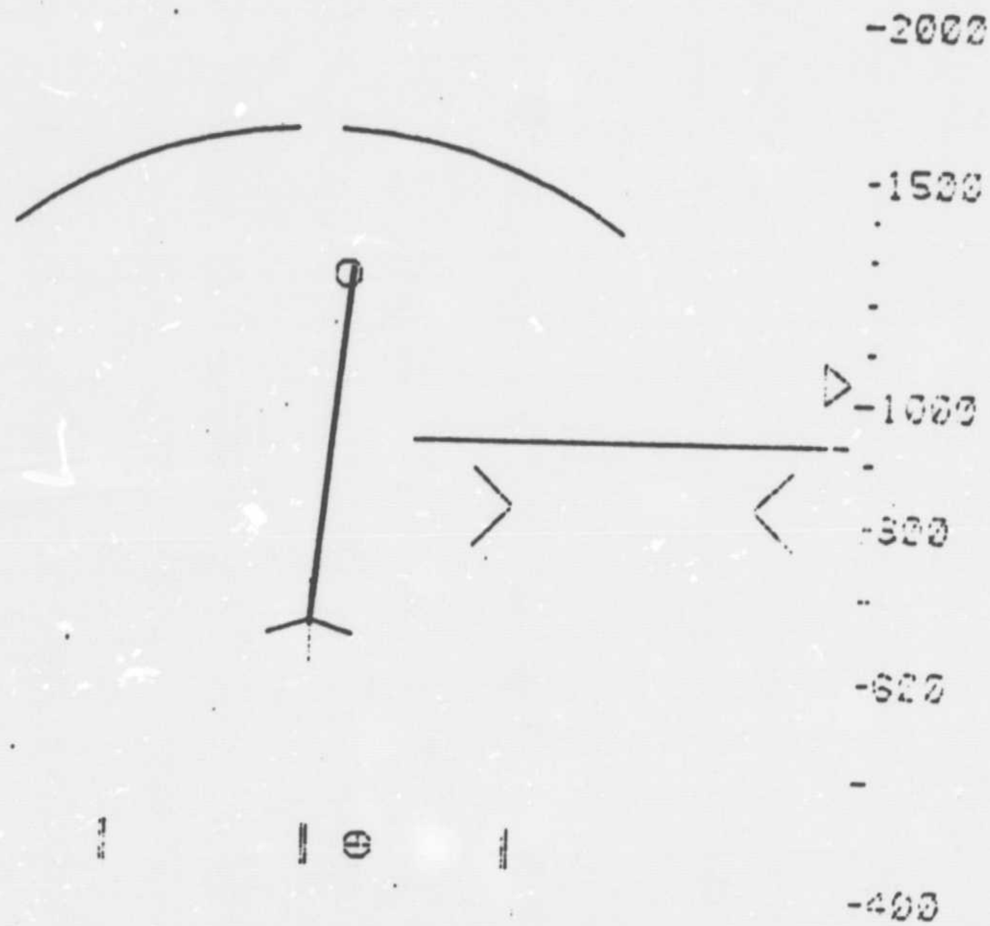

Figure 16.

<u>Velocity Vector</u>: The velocity vector is displayed as a line originating from the center of the aircraft position cursor/helicopter symbol and extending linearly in the velocity of the helicopter. The length of the vector is an indication of the speed the helicopter is moving toward the end of the vector. The velocity vector depicts actual helicopter movement while the acceleration vector displays an acceleration cue. The velocity vector is available in specified configurations and modes.

17→

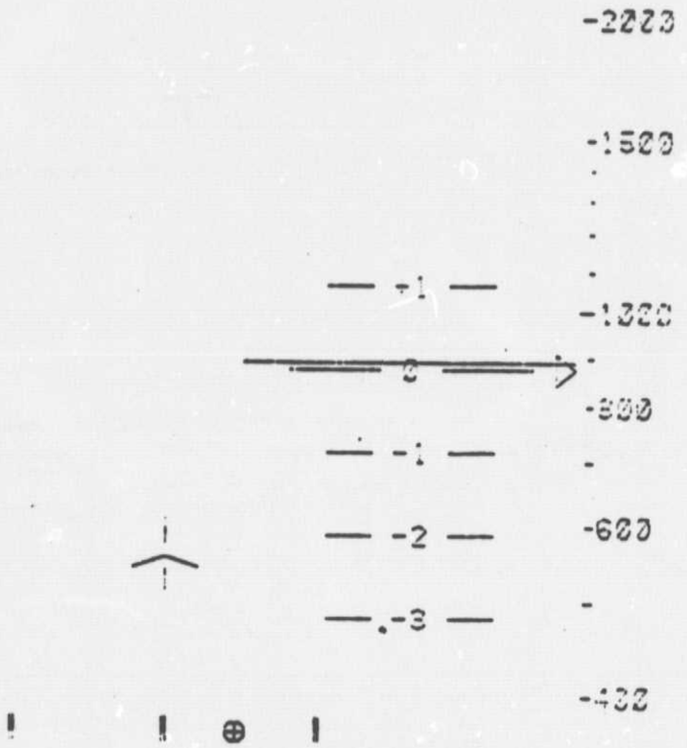

Figure 17.

Wind Speed and Direction: The speed and direction of the wind is depicted by a numerical readout of wind speed to the nearest knot coupled with an arrow that gives an indication of the direction of the wind relative to the heading of the helicopter. The wind speed and direction is available in all modes of specified configurations.

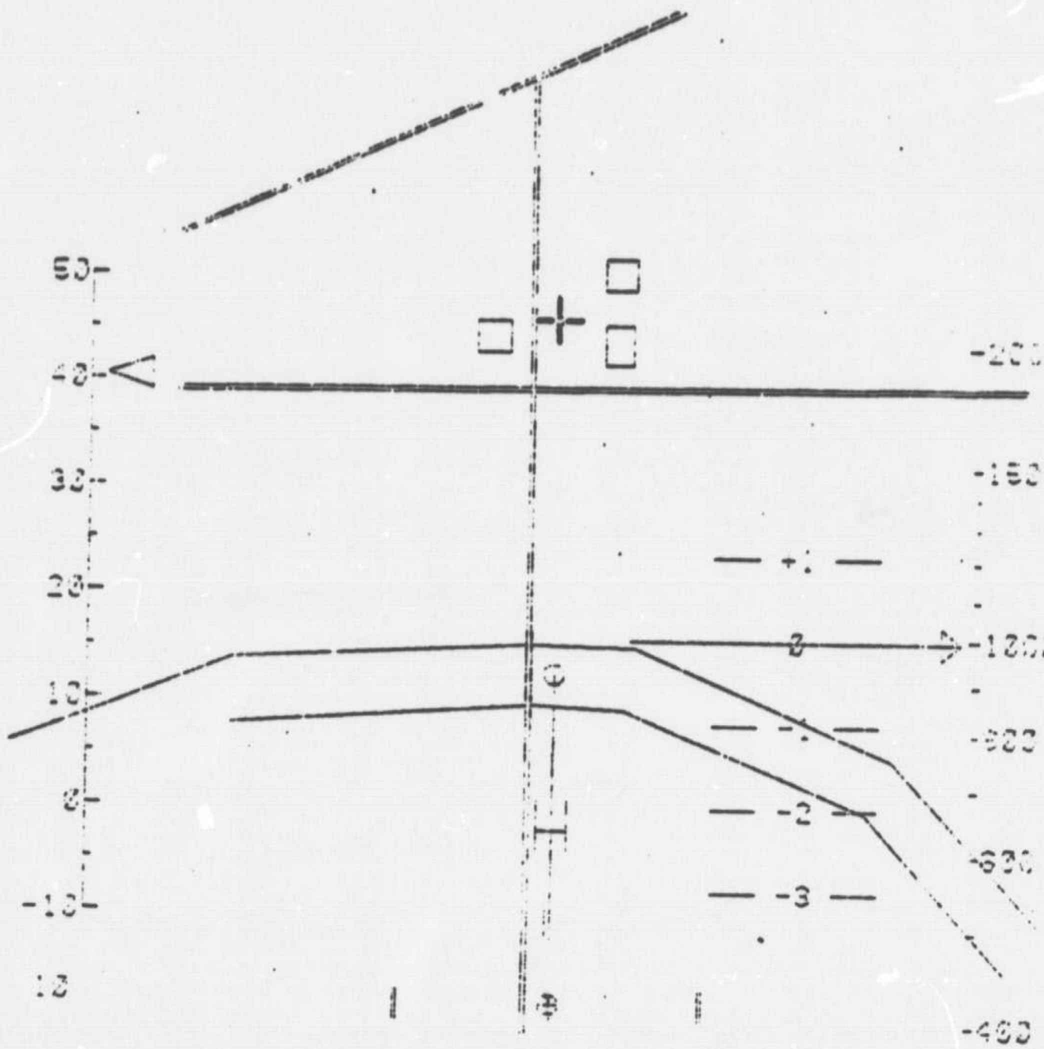

Figure 18.

<u>Beacon</u>: The beacon is designated by a fixed size open cross that is placed on the intended landing pad. The beacon is selectable and moveable by the pilot in all configurations and modes. Since it is always displayed at a fixed size the beacon is helpful in locating a landing area that is at extended range.

Figure 19.

Airspeed: True airspeed is present on the left side of the CRT using a linear fixed scale with a moving pointer. The upper limit is 50 knots forward with the lower limit being 10 knots rearward. The scale is incremented in 5 knot intervals.

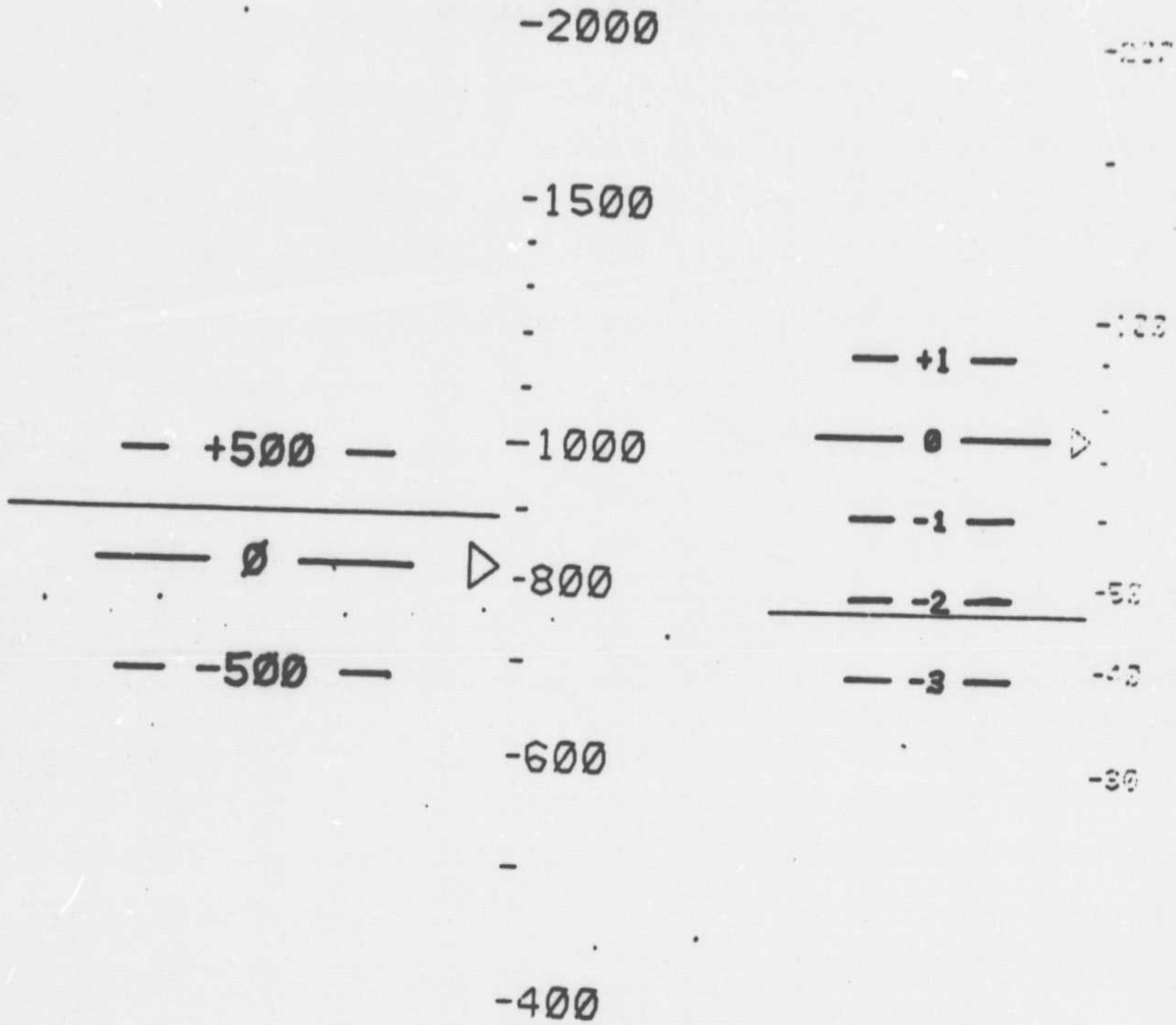

Figure 20.

<u>Expanded Vertical Speed</u>: The expanded vertical speed scale is presented on the right side of the CRT and works in conjunction with the vertical speed line. It is available with specified configurations and modes. The approach mode expanded scale will give an accurate rate of climb from -500 FPM to +500 FPM in a linear 500 FPM scale. The transition and hover modes display rate of climb from -3 FPS to +1 FPS in a linear 1 FPS mode. The expanded vertical speed scale is present in selected configurations during approach, transition and hover mode.

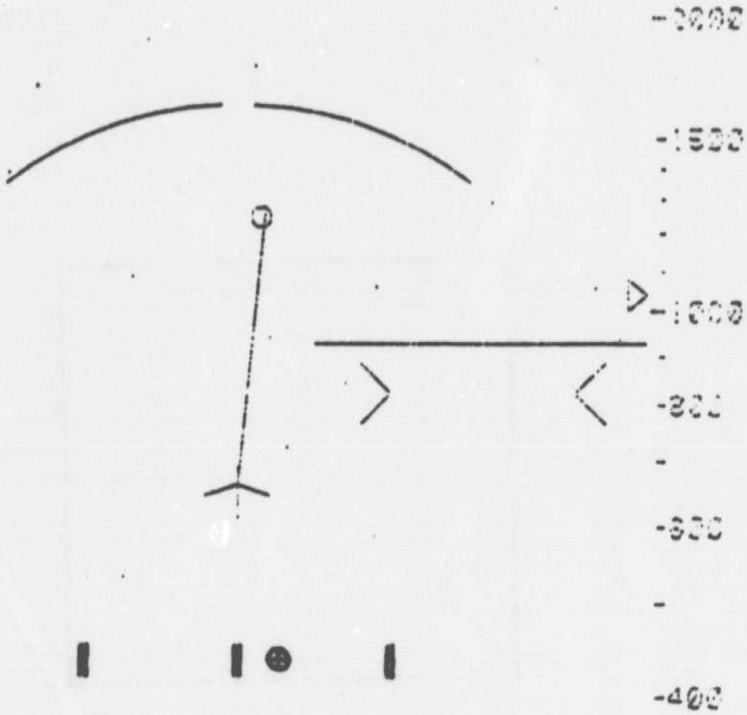

Figure 21.

<u>**Slip**</u>: **A computed slip angle representing the angle of the relative wind off the nose of the helicopter is depicted by a moving ball and three indices at the lower center of the CRT. The angle represented by the indices are 20° left or right. The slip angle indication is present in all configurations and modes when airspeed is above 15 knots.**

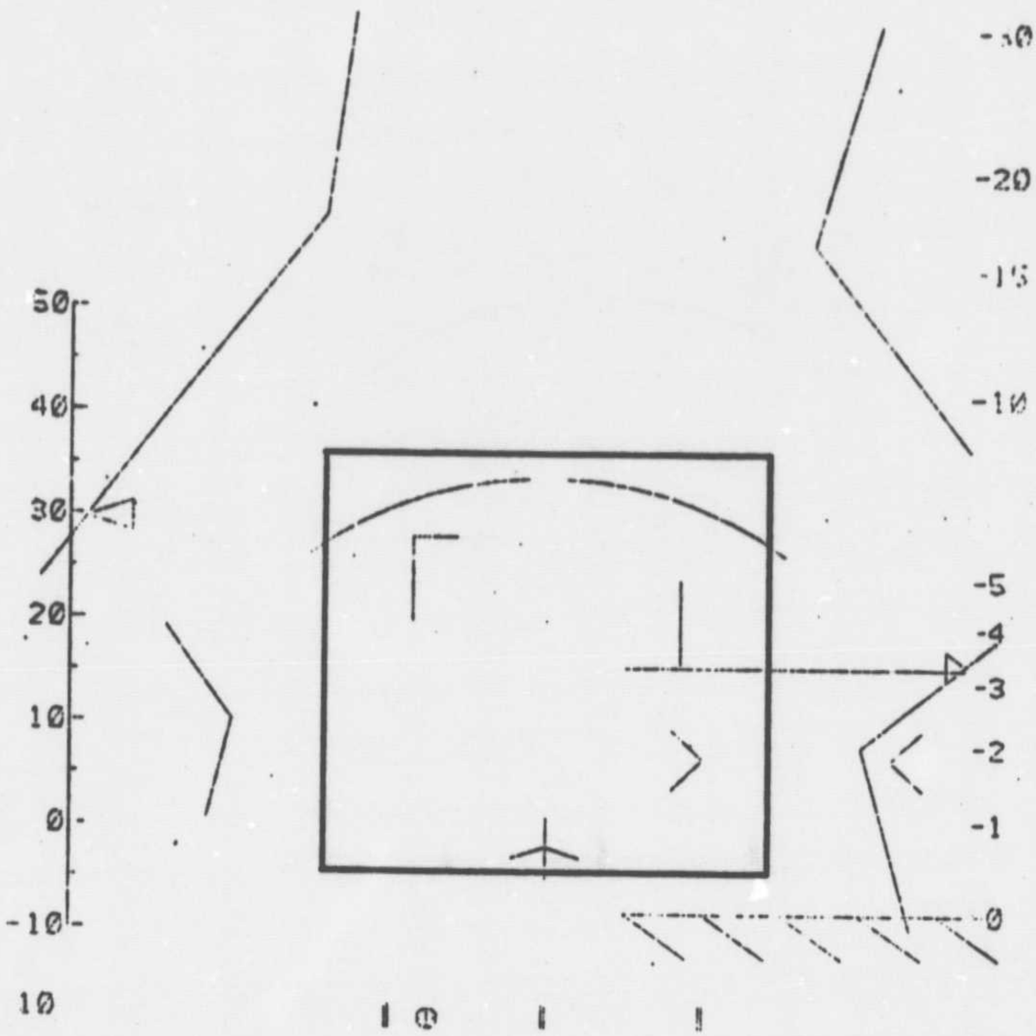

Figure 22.

Pad 1/2 Screen: The 100 foot square landing pad is presented by means of an expanding scale in all configurations during the approach, transition and hover modes. When the helicopter is on the ground the landing pad will fill 1/2 of the CRT. During the cruise and entry mode the landing panel is displayed at a fixed specified scale.

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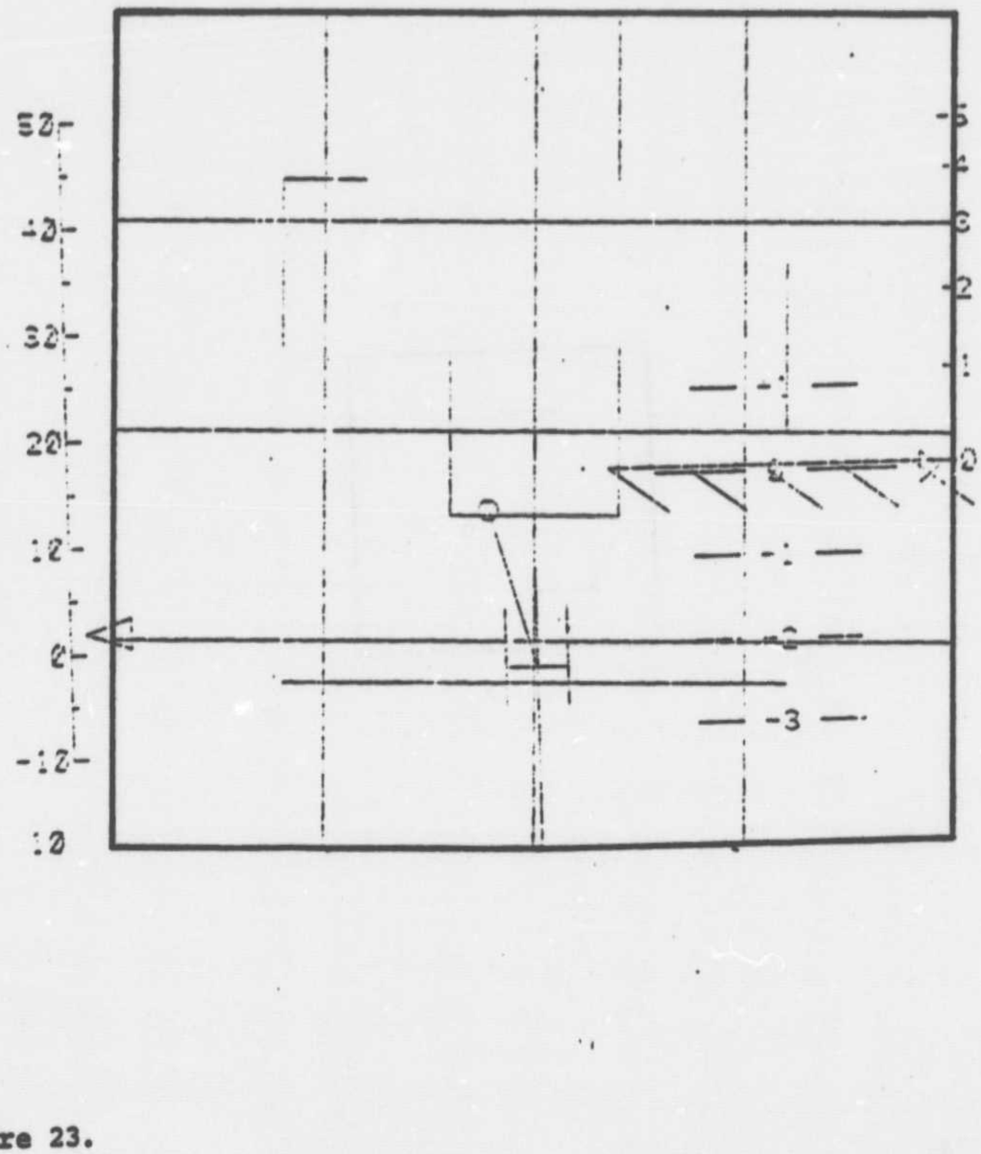

Figure 23.

Pad Full Screen: The 100 foot square landing pad is displayed by means of an expanding scale in all configurations during the approach, transition and hover modes. When the helicopter is on the ground the landing pad will fill the entire screen of the CRT. During cruise and entry modes the landing pad is presented at a specified fixed scale.

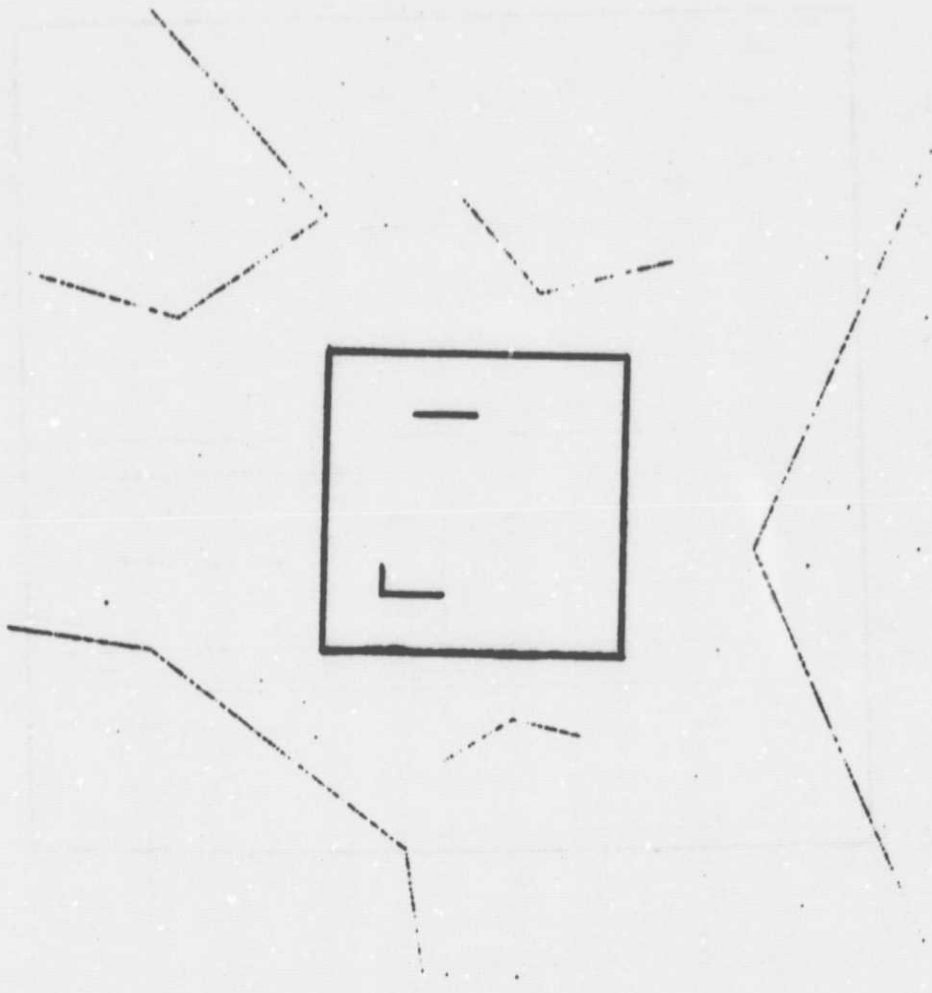

Figure 24.

<u>Minimum Texture</u>: The minimum texture display represents the minimum acceptable ground resolution that will be presented on the CRT. Texture is available in all configurations and modes but is displayed as a function of altitude.

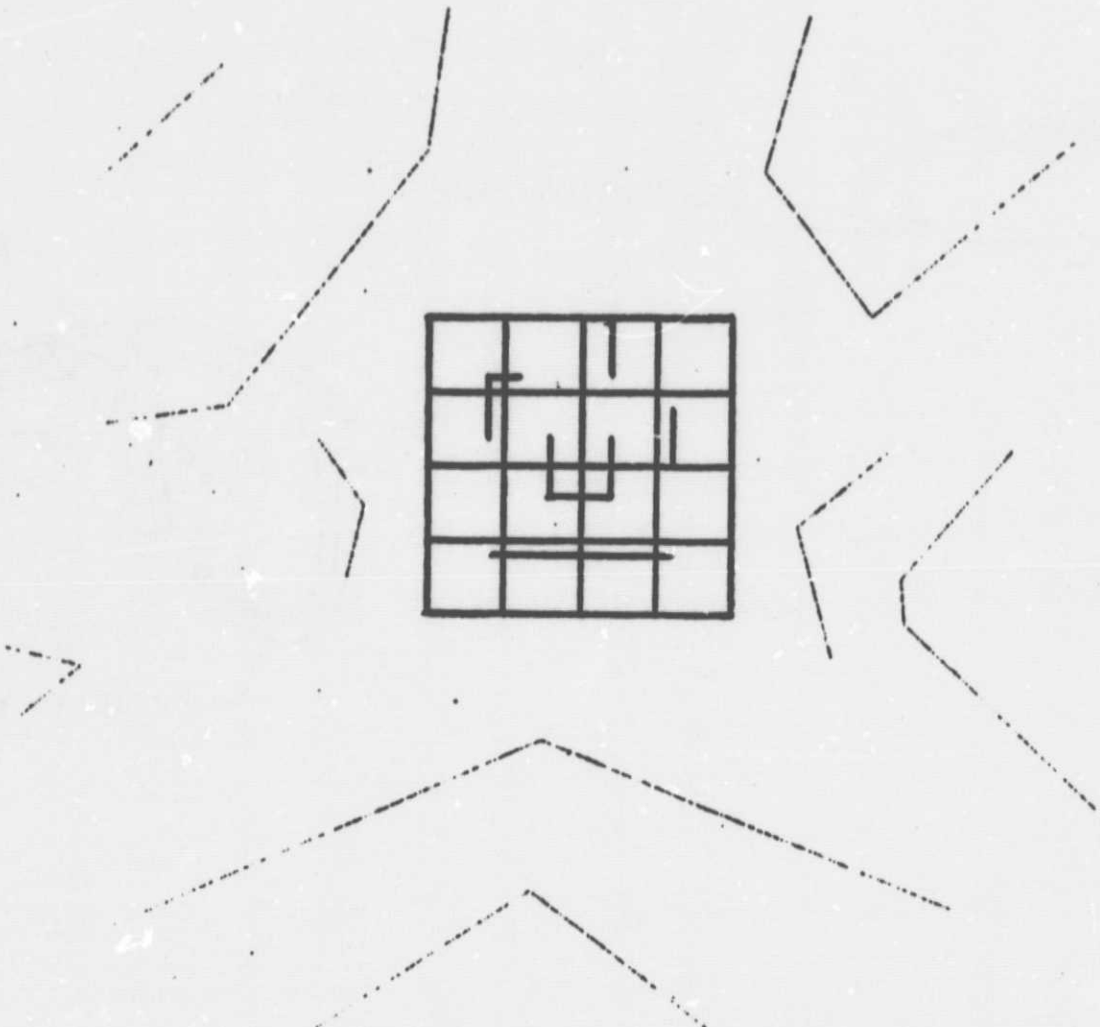

Figure 25.

Maximum Texture: The maximum texture display draws enhanced resolution and represents a more acceptable view to the pilot when he is maneuvering close to the ground. Texture is selectable in all configurations and modes but is displayed as a function of altitude.

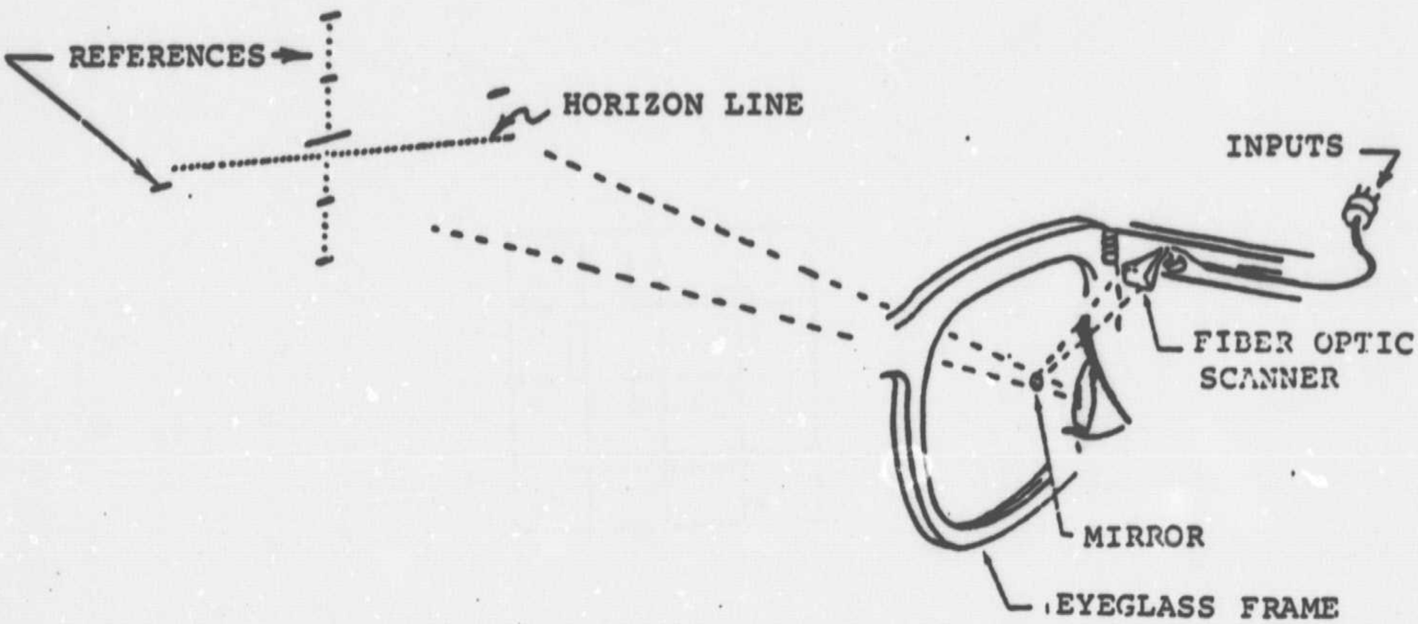

Figure 26.

<u>Micro Hud</u>: The micro hud is an optical device attached to a pair of eyeglass frames that presents the pilot with an artificial horizon. Since the micro hud is a seperate piece of hardware it is available in all configurations and modes, however for the purpose of this study, it will only be utilized in one configuration.

4.2 TRAINING PROCEDURES

The Subjects (Ss) will include 4-6 Test Pilots from Bell Helicopter Textron and possibly 1 Test Pilot from NASA Ames. Each (Ss) will be given a briefing on the purpose of the study before being asked to take the pilot's seat in the simulator cockpit. The (Ss) will be familiarized with the cockpit controls and the CRT. The visual displays will then be turned on and a short demonstration displayed. This demonstration task will allow each (Ss) to become familar with the visual presentation, the controls and the approach, transition to hover, hover and touchdown modes of the display.

At this time, training will begin with one of the four training configurations being presented. All extraneous variables will be held as constant as possible. Each (Ss) will be trained from 6-8 hours on the four different training configurations. Each (Ss) must successfully complete two touchdowns on each of the training configurations as a minimum criterion to progress into the testing phase of the study. The Experimenter Pilot, will make the judgement as to whether or not each pilot is ready to proceed on to the test phase.

A copy of the Test Pilot's Flight Experience/Certification questionnaire is shown as Figure 27.

Licenses/Certificates	Date of Certification
Commercial	
Fixed	________________
Rotory	________________
ATP	
Fixed	________________
Rotory	________________
CFI	
Fixed	________________
Rotory	________________
CFII	
Fixed	________________
Rotory	________________

Number of total hours in each of the following:

Fixed Wing	________ hours
Rotory	________ hours
Last Six Months	
Fixed	________ hours
Rotory	________ hours
VFR	________ hours
IFR	________ hours
Simulators	
Fixed	________ hours
Motion Base	________ hours

Experience using HUDs? Yes _____ No_____

If Yes, how many hours? __________ hours

Military Flight Experience? Yes _____ No_____

Number of years as a Test Pilot? ____________ years

In Fixed Wing? ______________ years

In Rotory Wing? ______________ years

Name ________________________ **Organization** ____________________________

Age ____________

Figure 27. Test Pilot's Flight Experience/Certification.

4.3 FORMAL TESTS

The test conditions represent selected candidate systems for the simulated radar imaging display (SRID). Figure 28 illustrates the primary test conditions.

For evaluation of the micro-HUD, a simple comparison will be made between the pilot flying the approach maneuvers with and without attitude data being presented on the micro-HUD. The basic SRID with selected symbology will be used and the single variable will be the micro-HUD. Presentations will be balanced. The data to be presented on the micro-HUD will be attitude.

The micro-HUD display provides information in traditional heads-up form. In this application it is used to superimpose attitude data on the simulated imaging display to provide a continuous attitude reference to the pilot thereby minimizing scan time.

4.4 DESCRIPTION OF EXPERIMENTAL CONDITIONS

The eleven experimental conditions are discussed below and the display configurations are outlined in matrix form in Figure 29. Symbol conditions were selected (1) to represent increased order of complexities and (2) because of programming and software limitations.

MISSION AIDS	MODES					
	CRUISE	ENTRY	APPROACH	TRANSITION	HOVER	OTHER
RADAR ALTITUDE SCALE	Fixed 2.5	Fixed 1.5	Expanding	Expanding	Expanding	
VERTICAL SPEED SCALE			X	X		
VERTICAL SPEED COMMAND POINTER			X	X		
GLIDESLOPE CURSOR			X	X		
AIRCRAFT POSITION CURSOR	X	X	X	X	X	
HELICOPTER SYMBOL				X	X	In selected modes will replace aircraft symbol
ACCELERATION VECTOR			X	X	X	Not available in approach mode in configuration C-12
VELOCITY VECTOR			X	X	X	Not available in approach mode in configuration C-12
WIND SPEED AND DIRECTION	X	X	X	X	X	
BEACON	X	X	X	X	X	Seperate switch function as selected by pilot
AIRSPEED	X	X	X	X	X	
EXPANDED VERTICAL SCALE			X	X	X	
SLIP	X	X	X	X	X	
PAD 1/2 SCREEN				X	X	Must be selected prior to commencing flight
PAD FULL SCREEN				X	X	Must be selected prior to commencing flight
MINIMUM TEXTURE	X	X	X	X	X	Must be selected prior to commencing flight
MAXIMUM TEXTURE	X	X	X	X	X	Must be selected prior to commencing flight
MICRO HUD	X	X	X	X	X	Seperate piece of equipment

Figure 28. Primary Test Conditions.

MISSION AIDS	CONFIGURATION CODE										
	1	2	3	4	5	6	7	8	9	10	11
Radar Altitude Scale	X	X	X	X	X	X	X	X	X	X	X
Vertical Speed Scale	X	X	X	X	X	X	X	X	X	X	X
Vertical Speed Command Pointer	X	X	X	X	X	X	X	X	X	X	X
Glideslope Cursor	X	X	X	X	X	X	X	X	X	X	X
Aircraft Position Cursor	X	X	X	X	X	X	X	X	X	X	X
Helicopter Symbol									X	X	X
Acceleration Vector							X	X	X	X	X
Velocity Vector							X	X	X	X	X
Wind Speed and Direction				X	X	X	X	X	X	X	X
Beacon	X	X	X	X	X	X	X	X	X	X	X
Airspeed	X	X	X	X	X	X	X	X	X	X	X
Expanded Vertical Speed				X	X	X				X	X
Slip	X	X	X	X	X	X	X	X	X	X	X
Pad 1/2 Screen	X	X		X	X		X	X	X	X	X
Pad Full Screen			X			X		X			
Minimum Texture	X			X			X			X	
Maximum Texture		X	X		X	X		X	X		X
Micro Hud											X

Figure 29. Configuration Matrix.

CONDITION 1

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
BEACON
AIRSPEED
SLIP
EXPANDING LANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MINIMUM GROUND TEXTURE

CONDITION 2

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM

RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE

VERTICAL SPEED

VERTICAL SPEED COMMAND POINTER

GLIDESLOPE

AIRCRAFT POSITION

WIND SPEED AND DIRECTION

BEACON

AIRSPEED

EXPANDED VERTICAL SPEED

SLIP

EXPANDING LANDING PAD TO 1/2 SCREEN ON TOUCHDOWN

MINIMUM GROUND TEXTURE

CONDITION 3

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
ACCELERATION VECTOR
VELOCITY VECTOR
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MINIMUM GROUND TEXTURE

CONDITION 4

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
HELICOPTER SYMBOL
ACCELERATION VECTOR
VELOCITY VECTOR
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
EXPANDING VERTICAL SPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MINIMUM GROUND TEXTURE

CONDITION 5

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM

RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE

VERTICAL SPEED

VERTICAL SPEED COMMAND POINTER

GLIDESLOPE

AIRCRAFT POSITION

AIRSPEED

SLIP

EXPANDING LANDING PAD TO 1/2 SCREEN ON TOUCHDOWN

MAXIMUM GROUND TEXTURE

CONDITION 6

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
EXPANDING VERTICAL SPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MAXIMUM GROUND TEXTURE

CONDITION 7

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
HELICOPTER SYMBOL
ACCELERATION VECTOR
VELOCITY VECTOR
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
SLIP
EXPANDING LANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MAXIMUM GROUND TEXTURE

CONDITION 8

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM

RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE

VERTICAL SPEED

VERTICAL SPEED COMMAND POINTER

GLIDESLOPE

AIRCRAFT POSITION

BEACON

AIRSPEED

SLIP

EXPANDING LANDING PAD TO 1/2 SCREEN ON TOUCHDOWN.

MAXIMUM GROUND TEXTURE

CONDITION 9

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
EXPANDED VERTICAL SPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MAXIMUM GROUND TEXTURE

CONDITION 10

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
ACCELERATION VECTOR
VELOCITY VECTOR
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MAXIMUM GROUND TEXTURE

CONDITION 11

VARIABLES:

ATTITUDE COMMAND CONTROL SYSTEM
RATE COMMAND CONTROL SYSTEM

CRT SYMBOL PRESENTATION:

RADAR ALTITUDE
VERTICAL SPEED
VERTICAL SPEED COMMAND POINTER
GLIDESLOPE
AIRCRAFT POSITION
HELICOPTER SYMBOL
ACCELERATION VECTOR
VELOCITY VECTOR
WIND SPEED AND DIRECTION
BEACON
AIRSPEED
EXPANDING VERTICAL SPEED
SLIP
EXPANDING PAD TO 1/2 SCREEN ON TOUCHDOWN
MAXIMUM GROUND TEXTURE

ADDITIONAL DEVICES:

MICRO HUD

5. DATA COLLECTION/ANALYSIS

Prior to testing, helicopter pilots experienced in the Model 222 weight class helicopter will be asked to evaluate the simulated cockpit to assure the experimenters that the simulator "flies" like a helicopter. To do this, pilots will be asked to fly specified maneuvers and then provide their comments on the questionnaire shown in Figure 30.

5.1 Quantification

Data to be collected during simulated flight will include the following:

a. Touchdown. The following data will be recorded relative to touchdown:

1. Vertical velocity
2. Lateral velocity
3. Forward velocity
4. Pitch attitude
5. Roll attitude
6. Heading in relation to the desired reference
7. Position in relation to the center of the pad.

Name ____________________

SAMPLE

PRETEST

PILOT QUESTIONNAIRE

SUBJECTIVE SIMULATOR EVALUATION

Please rate your answers on a scale of 1 to 5.	GOOD 1 - 2 - 3 - 4 - 5 POOR
1. Overall feel of the simulator to fly like a medium-sized helicopter.	________
2. The feel of the simulator to fly like a helicopter in the following maneuvers:	
Cruise	________
Turns	________
Climbs	________
Descents	________
Transition to Hover	________
Hover	________
3. Please rate your subjective feelings about the individual controls.	
Collective	________
Cyclic-lateral	________
Cyclic-fore/aft	________
Pedals	________
4. If any of the controls are not considered by you to be acceptable, please list what you consider to be the areas of unacceptability.	
(a) Built in control friction:	
Collective	________
Cyclic-lateral	________
Cyclic-fore/aft	________
Pedals	________

Figure 30. Pretest Pilot Questionnaire. (Sheet 1 of 2)

SAMPLE

Pretest Pilot Questionnaire
Subjective Simulator Evaluation

GOOD 1 - 2 - 3 - 4 - 5 POOR

(b) Time of response of instruments to control input:

Collective	________
Cyclic-lateral	________
Cyclic-fore/aft	________
Pedals	________

(c) Control movement null areas:

Collective	________
Cyclic-lateral	________
Cyclic-fore/aft	________
Pedals	________

(d) Other:

Figure 30. (Sheet 2 of 2)

5.2 SUBJECTIVE EVALUATION

The experiments will be randomly selected for each subject with the exception of the six full pad, hi-texture conditions which will be randomized within and run sequentially.

After each subject completes a configuration condition, a Subjective Simulator Evaluation questionnaire will be filled out. Samples of the questionnaires are shown in Figure 31 through 47. An overall subjective score will be developed from these questionnaires and used to derive relative merit comparisons between the display configurations.

5.3 DATA ANALYSIS

Data will be reduced and presented in graphic form using nonparametric measures as appropriate. It is anticipated that small-sample statistics will be utilized, that no fewer than four subjects will be employed in these tests, and that all subjects will be qualified as helicopter pilots.

The results of these tests should permit the research personnel to assess the validity of the experimental conditions and also the displays.

SUBJECTIVE SIMULATOR EVALUATION QUESTIONNAIRE

NAME: ____________________________ CONFIGURATION: ________________________

We would like to get your opinion on various aspects of the displays and formats used in these tests. If you place a mark at less than optimum, please note what aspects of the display were unsatisfactory.

RADAR ALTITUDE SCALE:

(1) Location of the Radar Altitude Scale.

Unsatisfactory Satisfactory Optimum

Suggested changes: ____

(2) Display format of Radar Altitude Scale.

Unsatisfactory Satisfactory Optimum

Suggested changes: ____

Figure 31. Radar Altitude Scale Form.

VERTICAL SPEED SCALE:

(1) The Vertical Speed Display.

Unsatisfactory Satisfactory Optimum

Comments:

Figure 32. Vertical Speed Scale Form.

VERTICAL SPEED COMMAND POINTER:

(1) The location of the Vertical Speed Command Pointer.

Unsatisfactory Satisfactory Optimum

(2) Is the information presented by the vertical speed command pointer a valuable aid?

Yes _____ No _____

Comments: ______

Figure 33. Vertical Speed Command Pointer Form.

GLIDESLOPE CURSOR:

(1) Did you find the glideslope cursor helpful during the approach?

Yes _____ No _____

Suggested changes: ____

____

____

____

____

____

____

____

____

(2) In conjunction with the vertical speed command pointer, did the glideslope cursor present adequate information for the approach portion of the flight?

Yes _____ No _____

Comments: ____

____

____

____

____

____

____

____

____

Figure 34. Glideslope Cursor Form.

AIRCRAFT POSITION CURSOR:

(1) The Aircraft Position Cursor.

Unsatisfactory Satisfactory Optimum

Suggested changes: ____________________

(2) During the approach did you feel you were inside the helicopter looking out at the scenario?

Yes _____ No _____

Comments: ____________________

Figure 35. Aircraft Position Cursor Form.

HELICOPTER SYMBOL:

(1) The location of the Helicopter Symbology on the CRT.

Unsatisfactory ——— Satisfactory ——— Optimum

Suggested changes: ____________________

____

____

____

____

____

____

____

____

(2) Did the helicopter symbol assist controlability during the transition and hover modes of flight?

Yes _____ No _____

(3) If answer to #2 is no, was the helicopter symbol better or worse than the aircraft symbol?

Better __________
Worse __________

Comments: ____________________

____

____

____

____

____

____

____

____

Figure 36. Helicopter Symbol Form.

ACCELERATION VECTOR:

(1) Did the acceleration vector assist in the successful completion of the approach, transition and hover modes?

Unsatisfactory — Satisfactory — Optimum

(2) Did the acceleration vector assist in acceptable touchdown velocities?

Unsatisfactory — Satisfactory — Optimum

(3) Is the acceleration vector necessary to successfully complete the full stop approach?

Unsatisfactory — Satisfactory — Optimum

Comments: ____

Figure 37. Acceleration Vector Form.

VELOCITY VECTOR:

(1) Was the velocity vector important in the successful completion of the approach, transition and hover modes?

Unsatisfactory Satisfactory Optimum

(2) Was the velocity vector important in assisting to acceptable touchdown velocities?

Unsatisfactory Satisfactory Optimum

(3) Was the velocity vector necessary to successfully complete the full stop approach?

Unsatisfactory Satisfactory Optimum

(4) Was the information presented by the acceleration vector in conjunction with the velocity vector easy to understand?

Unsatisfactory Satisfactory Optimum

Comments: ____

____

____

____

____

____

____

____

____

Figure 38. Velocity Vector Form.

BEACON:

(1) Did you use the beacon during the approach?

Yes _____ No _____

(2) If #1 is YES, the Beacon was:

Unsatisfactory — Satisfactory — Optimum

(3) If #1 is NO, why didn't you use the beacon. ____________________

____

____

____

____

____

Figure 39. Beacon Form.

AIRSPEED:

(1) In your opinion was the airspeed presented in the most optimum position?

Unsatisfactory Satisfactory Optimum

(2) In your opinion was the airspeed presented in the most optimum way?

Unsatisfactory Satisfactory Optimum

(3) Would you rather have a nonlinear scale at lower speeds?

Unsatisfactory Satisfactory Optimum

Comments: ______________________________

Figure 40. Airspeed Form.

EXPANDED VERTICAL SPEED:

(1) In your opinion, the location of the expanded vertical speed information was:

Unsatisfactory Satisfactory Optimum

(2) Is the expanded vertical speed information adequate to assist in accomplishing the full stop approach?

Unsatisfactory Satisfactory Optimum

(3) Do you feel the expanded vertical speed information is necessary to accomplish the full stop approach?

Yes _____ No _____

Comments: ____

____

____

____

____

____

____

____

____

Figure 41. Expanded Vertical Speed Form.

SLIP:

(1) The information presented by the slip indicator was:

Unsatisfactory Satisfactory Optimum

Comments: ______________________________

Figure 42. Slip Form.

PAD 1/2 SCREEN:

(1) Was the scaling of the pad adequate to give aircraft motion cues at a hover?

Unsatisfactory — — — Satisfactory — — — Optimum

(2) Did the pad scaling appear to be realistic?

Yes _____ No _____

(3) Did the expanding scale of the pad distract from the successful completion of touchdown?

Yes _____ No _____

Comments: ____

____

____

____

____

____

____

____

____

Figure 43. Pad 1/2 Screen Form.

PAD FULL SCREEN:

(1) Was the scaling of the pad adequate to give aircraft motion cues at a hover?

Unsatisfactory — Satisfactory — Optimum

(2) Did the pad scaling appear to be realistic?

Yes _____ No _____

(3) Did the expanding scale of the pad distract from the successful completion of touchdown?

Yes _____ No _____

Comments: ____

Figure 44. Pad Full Screen Form.

MINIMUM TEXTURE:

(1) Did the minimum texture display present adequate motion cues at a hover?

Unsatisfactory | Satisfactory | Optimum

Comments: ____

____

____

____

____

____

____

____

____

Figure 45. Minimum Texture Form.

<u>**MAXIMUM TEXTURE**</u>:

(1) **Did the maximum texture display present adequate motion cues at a hover?**

Unsatisfactory		Satisfactory			Optimum

Comments: ____

____

____

____

____

____

____

____

____

Figure 46. Maximum Texture Form.

MICRO-HUD:

(1) Was the information presented on the mirco-Hud helpful throughout the full stop approach? Yes _____ No _____

If answer is No explain why not: ______________________________

____

____

____

____

____

____

____

____

(2) If you could, would you like to have other information presented on the micro-Hud? Yes _____ No _____

Comments: ____

____

____

____

____

____

____

____

____

Figure 47. Micro-HUD Form.

APPENDIX B

CONTROL SYSTEM CONFIGURATION

APPENDIX B

CONTROL SYSTEM CONFIGURATION

The control system for the experimental system provided two modes of operation: ATTITUDE COMMAND and RATE COMMAND. Both modes provided attitude and heading hold. In the ATTITUDE-COMMAND mode, pitch and roll attitudes were commanded by stick displacement. In the RATE-COMMAND mode, the attitude rate was proportional to stick displacement. In this latter mode, a displacement of the stick also produced an essentially instantaneous attitude change. This provided a combined response that allowed the stick to remain in its trim position in steady state while making a constant turn, for example. This mechanism was designed to be compatible with a control system that keeps a direct mechanical link between the pilot and the swashplate, by way of one or more series servoactuators, and does not try to cancel the pilot's initial input motion. There was no difference between the modes in heading control.

<u>Heading Control System</u>. The cockpit pedal controls consisted of a set of standard Bell 222 pedals, a position sensor, and a centering spring. There was no force-measuring sensor or actuator. The control system was designed to provide a rate-command heading-hold system, making use of the pedals as a command generator and always operating about the spring-centered position. A threshold was used in the command path to account for centering error in the spring arrangement. The pedals were also connected by a direct path to the tail rotor to produce an essentially instantaneous pitch change. This was compatible with the actuation scheme, as in the pitch and roll axes. The overall configuration of the heading control did not provide a desirable response to pilot commands because of the inability of the centering spring to precisely center the pedals in the presence of friction. A 12-cm (0.5-inch) threshold was necessary to eliminate heading drift, and this made it difficult for the pilot to find a stable point for the pedals. For the formal experiment, however, a straight-in approach was used, and use of the pedals was almost entirely unnecessary. This allowed the experiment to proceed without interference.

Figure B-1 is a block diagram of the heading control system. The actuator loop model represents a position control loop having a second-order response with a bandwidth of 4.3 Hz and 0.8 damping factor, with an authority limit of 25%. The gains, shown below, provided a well-damped response to transient inputs (~0.7 damping factor):

Heading/pedal motion	6.6	deg/in
Rate/pedal motion	16.6	deg/sec/in
Pedal rate threshold	0.5	in
Heading error gain, δ_T/ψ	1.0	deg/deg
Heading error integral gain	0.05	1/sec
Rate gain, $\delta_T/\dot{\psi}$	0.3	deg/deg/sec

Figure B-2 shows response time histories taken from a simulated flight run, using pilot input to the pedals. The responses show the pedal input, heading (PSI), and heading rates (RB).

<u>Pitch and Roll Axis Controls</u>. The cockpit equipment included a system for providing a simulated feel to the controls, similar to that of an actual helicopter control system. It provided a capability to trim the stick to any position, with a preloaded spring gradient characteristic from the trim position. A trim-release button on the cyclic stick provided the trim-release command to the system. This command freed the stick from any centering gradients, leaving only a breakout friction characteristic similar to that of an actual helicopter. The force-trim system also contained provisions for beep-trim of stick position. This function was used to provide an alternate means of pilot input. The beep action was used for moving the stick, as well as for changing an internal attitude reference for the RATE-COMMAND mode. In the ATTITUDE-COMMAND mode, only the cockpit stick position was used to provide new attitude references. The block diagram in Figure B-3 shows the signal paths and logic used for both modes of operation. The ATTITUDE-COMMAND mode was provided by eliminating the signal paths involving stick motion as used to change an internal attitude reference. In the figure, the dashed lines denote logic controls analogous to relay control lines.

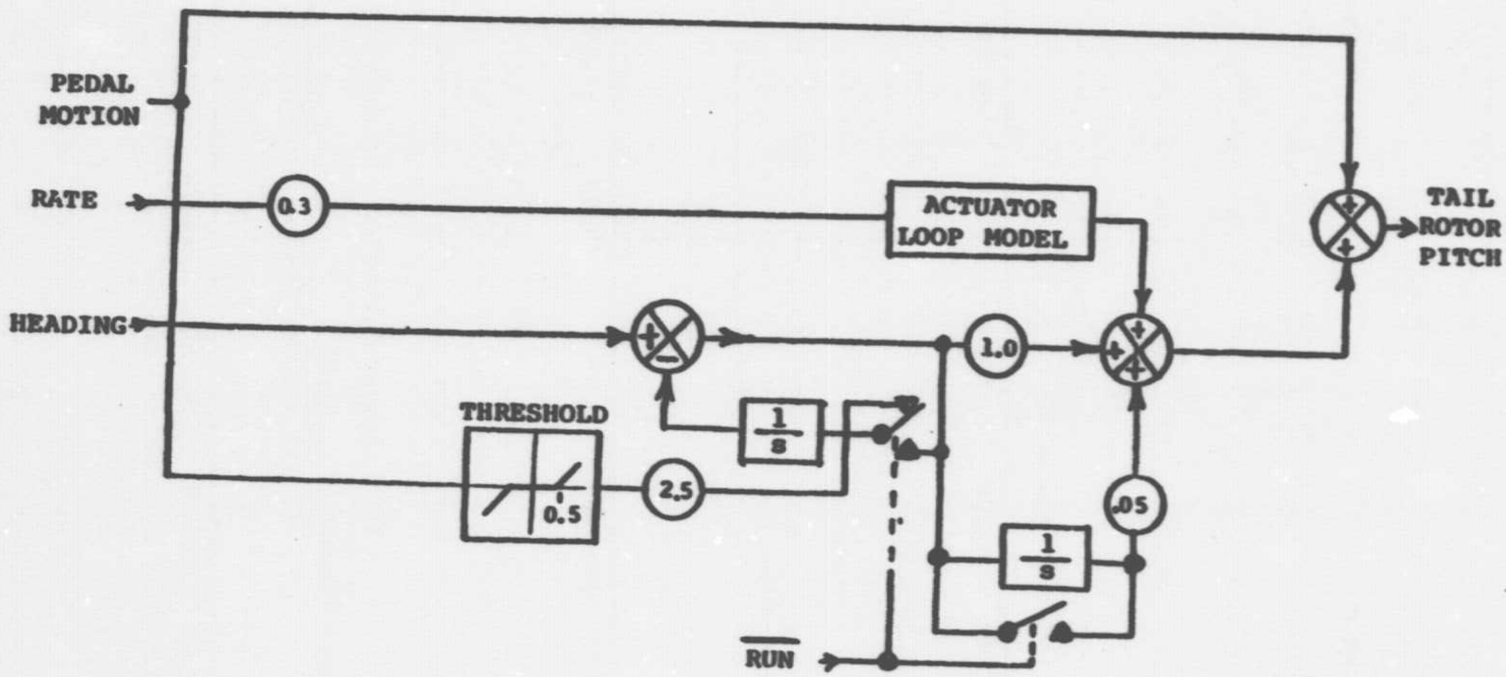

Figure B-1. Block diagram of heading/yaw control.

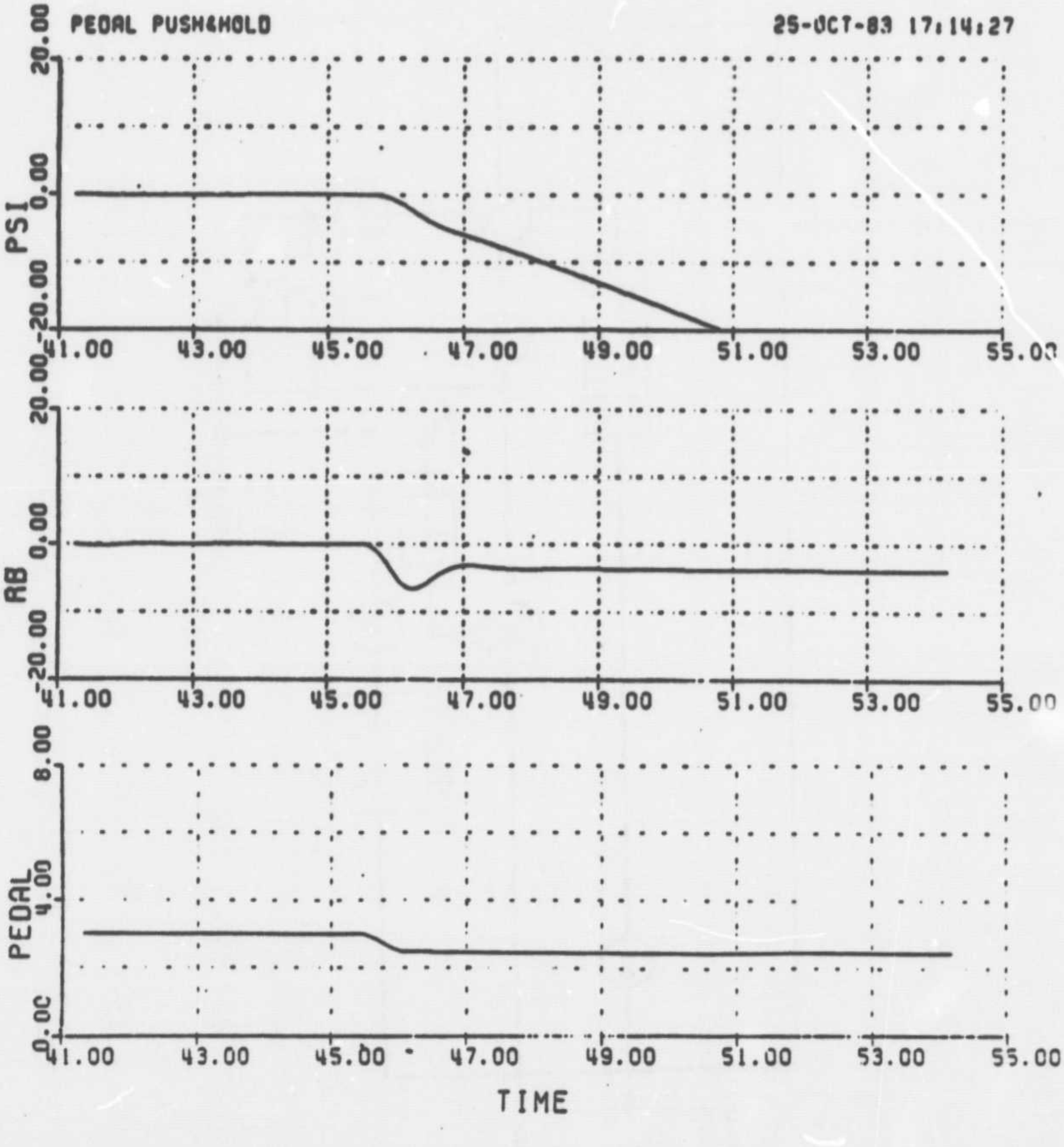

Figure B-2. Time history of heading (PHI) and heading rate (RB) response to pedal input.

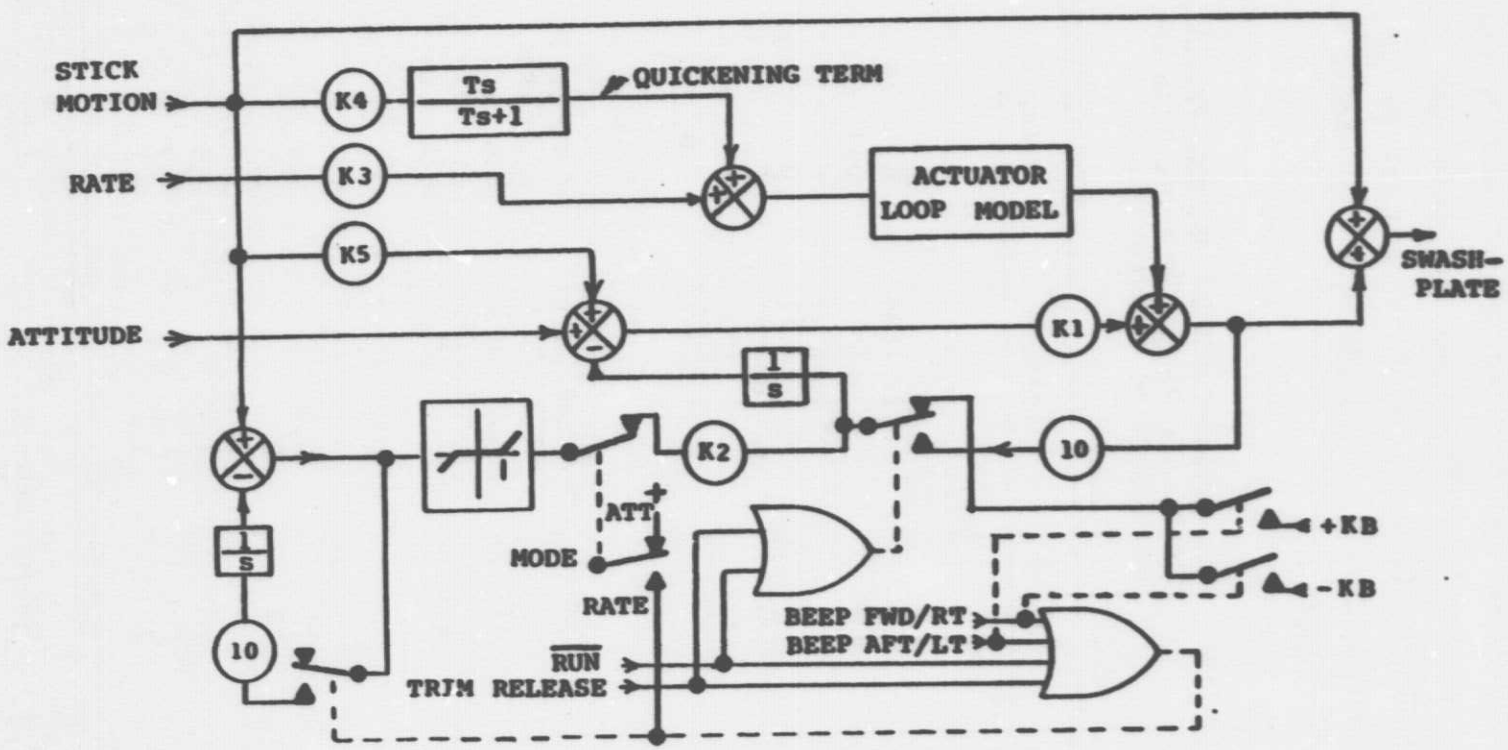

Figure B-3. Block diagram of pitch/roll controls.

Table B-1 lists the gains, time constants, and resulting closed loop gains for two system configurations called "production" and "postproduction." The production values were used in the formal test phase and yielded an attitude response having a large attitude overshoot produced by the quickening term. Later, parameters were modified to provide only a quickened attitude response, with little or no overshoot.

TABLE B-1. GAINS, TIME CONSTRAINTS, AND RESULTING CLOSED LOOP GAINS FOR PRODUCTION AND POSTPRODUCTION CONFIGURATIONS

Item	Config[1]	Lateral	Fore/Aft	Units
Open-loop gains				
Rate	P	-0.15 (K3)	0.3 (K3)	deg/deg/sec
	PP	-0.15 (K3)	0.4 (K3)	deg/deg/sec
Attitude		-0.2 (K1)	0.5 (K1)	deg/deg
Att command	P	0 (K5)	0 (K5)	deg/deg.
	PP	-3.25 (K5)	-1.25 (K5)	deg/deg
Rate command	P	5.0 (K2)	1.25 (K2)	deg/deg/sec
	PP	2.5 (K2)	2.5 (K2)	deg/deg/sec
Rate comm threshold		0.15 (TH)	0.15 (TH)	inch
Beep comm rate	P	0 (KB)	0 (KB)	R/sec
	PP	0.05 (KB)	0.05 (KB)	R/sec
Quickening comm	P	2.5 (K4)	0.4 (K4)	R/R
	PP	1.5 (K4)	0.4 (K4)	R/R
Quick time const	P	0.85 (T)	1.2 (T)	sec
	PP	0.5 (T)	0.6 (T)	sec
Closed-loop results				
Attitude comm	P	6.7	5.7	deg/in
	PP	2.3	2.1	deg/in
Rate comm	P	5	1.25	deg/sec/in
	PP	2.5	2.5	deg/sec/in
Beep	P	1.7	2.3	
	PP	2.3	3.1	

[1]P = production, PP = postproduction

Figure B-4 illustrates a time history of a step input in lateral cyclic (lateral push/hold) and the resulting response, in the production ATTITUDE-COMMAND mode. The attitude overshoot can be seen in the response of attitude (PHI), with the associated rates (PB) also shown. The pitch response was similar.

Figure B-5 illustrates the change in the postproduction response resulting from changes in system parameters.

Figure B-6 illustrates the response of the production RATE-COMMAND mode to an aft cyclic step input. The combined initial attitude (THET) command can be seen, along with the subsequent constant rate (QB).

Figure B-7 illustrates the postproduction response to an aft cyclic step input in the ATTITUDE-COMMAND mode. The slight long-term attitude change is due to trim change with airspeed change.

Collective Damping. The collective control was modified to provide a slightly damped velocity response to collective input. This was used to help offset the breakout friction that was necessary to hold the stick in position. The feedback was used in all modes and consisted of a pure velocity term of gain:

$$\delta_c/\Delta \dot{H} = 0.057 \text{ deg/ft}$$

This resulted in a computed stick sensitivity of approximately 32 ft/sec/in, assuming no inherent aerodynamic damping. The aerodynamic damping was considerably the greater of the two, so this feedback only slightly affected the response.

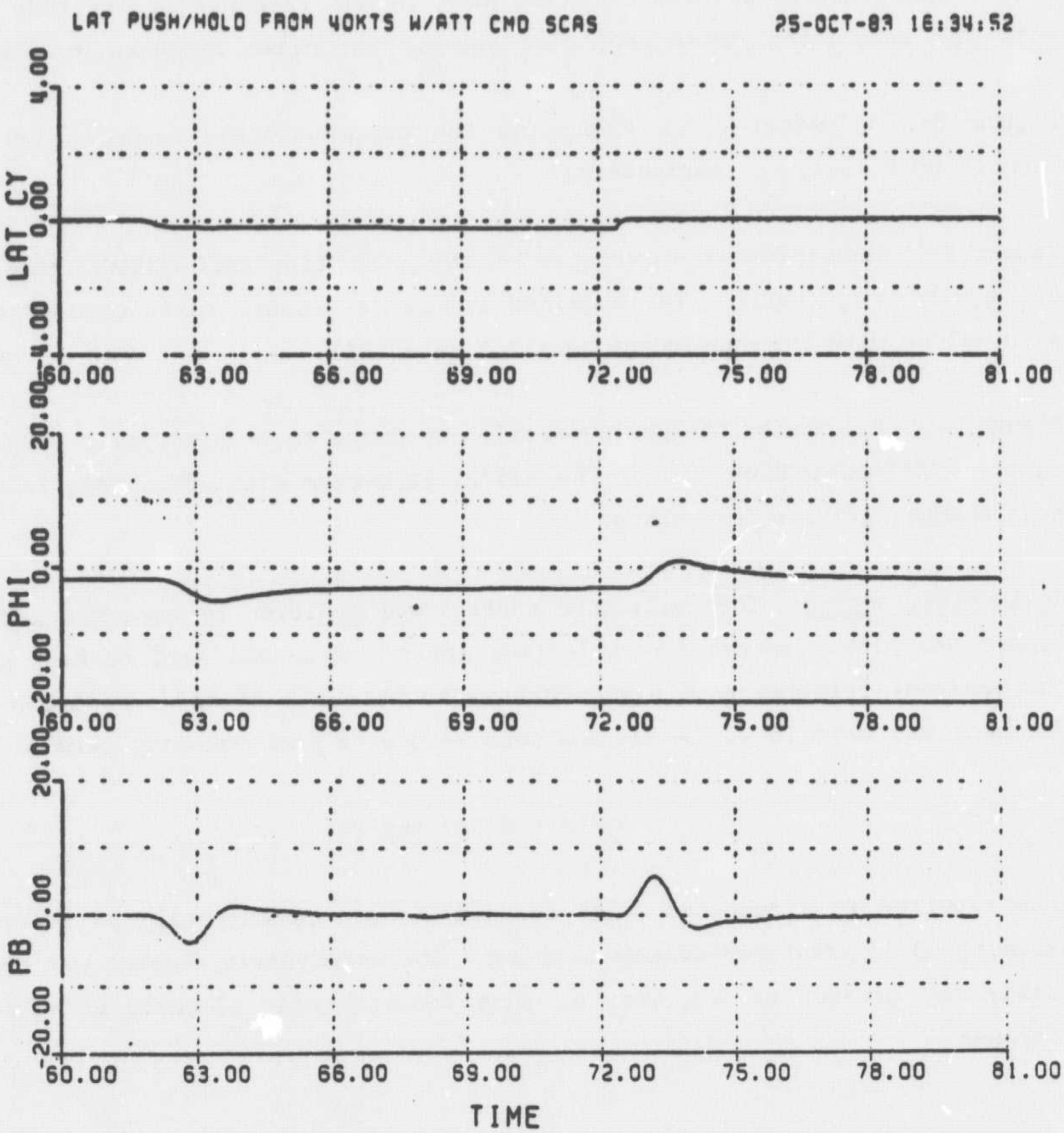

Figure B-4. Time history of attitude (PHI) and rates (PB) response to step input in lateral cyclic: production ATTITUDE-COMMAND mode.

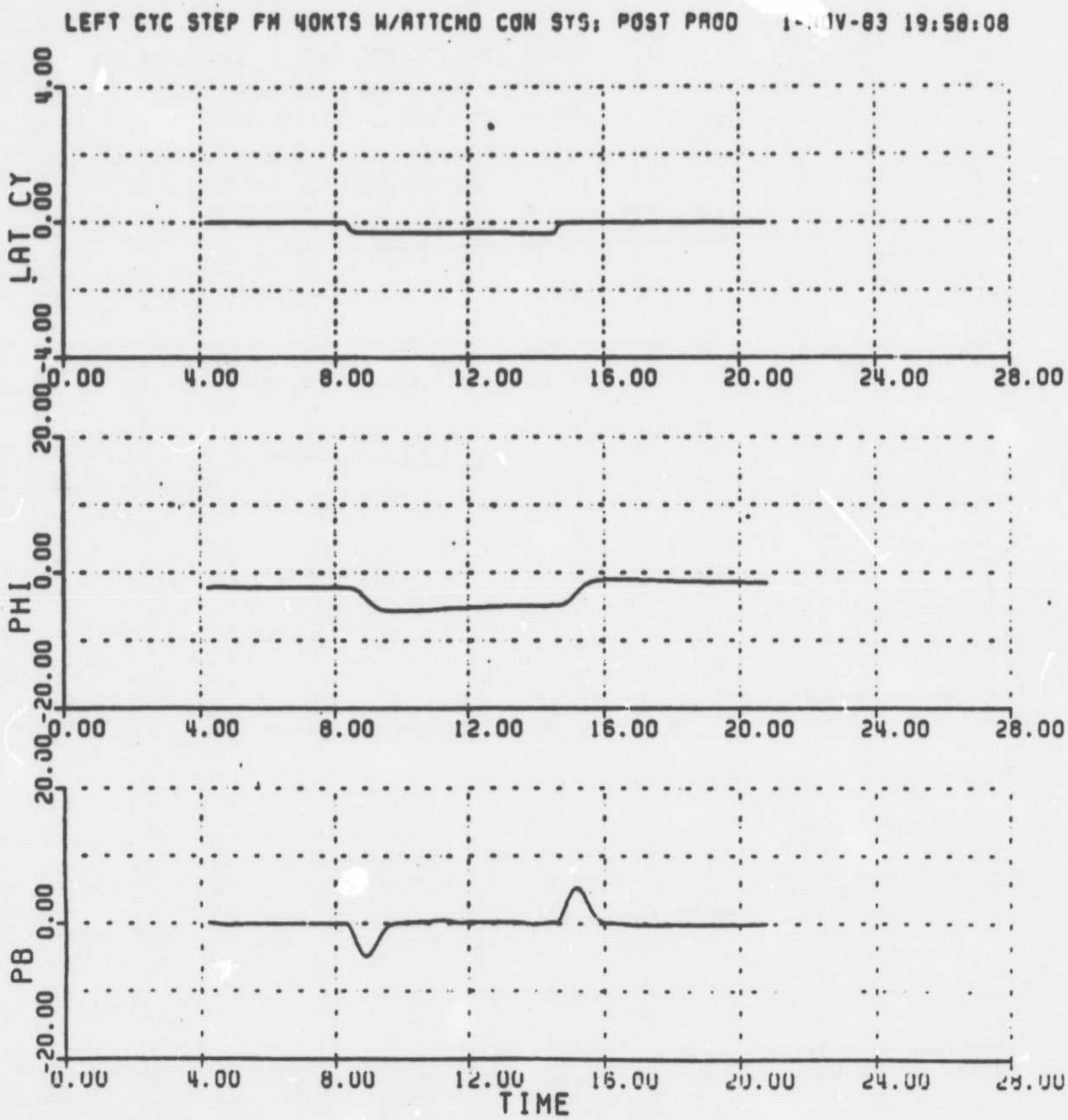

Figure B-5. Time history of attitude (PHI) and rates (PB) response to step input in lateral cyclic: postproduction ATTITUDE-COMMAND mode.

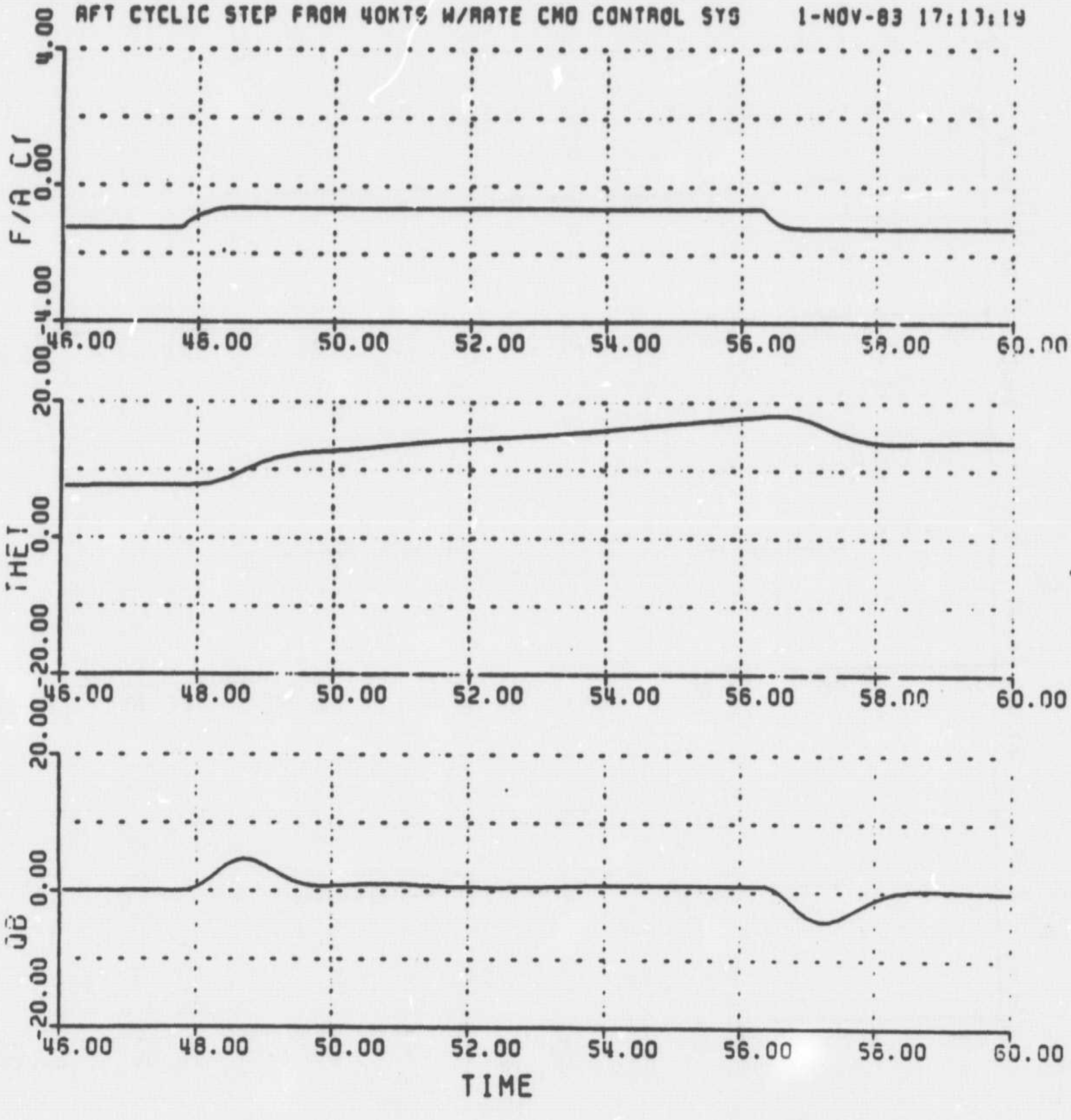

Figure B-6. Time history of attitude (THET) and rates (QB) response to step input in aft cyclic: production RATE-COMMAND mode.

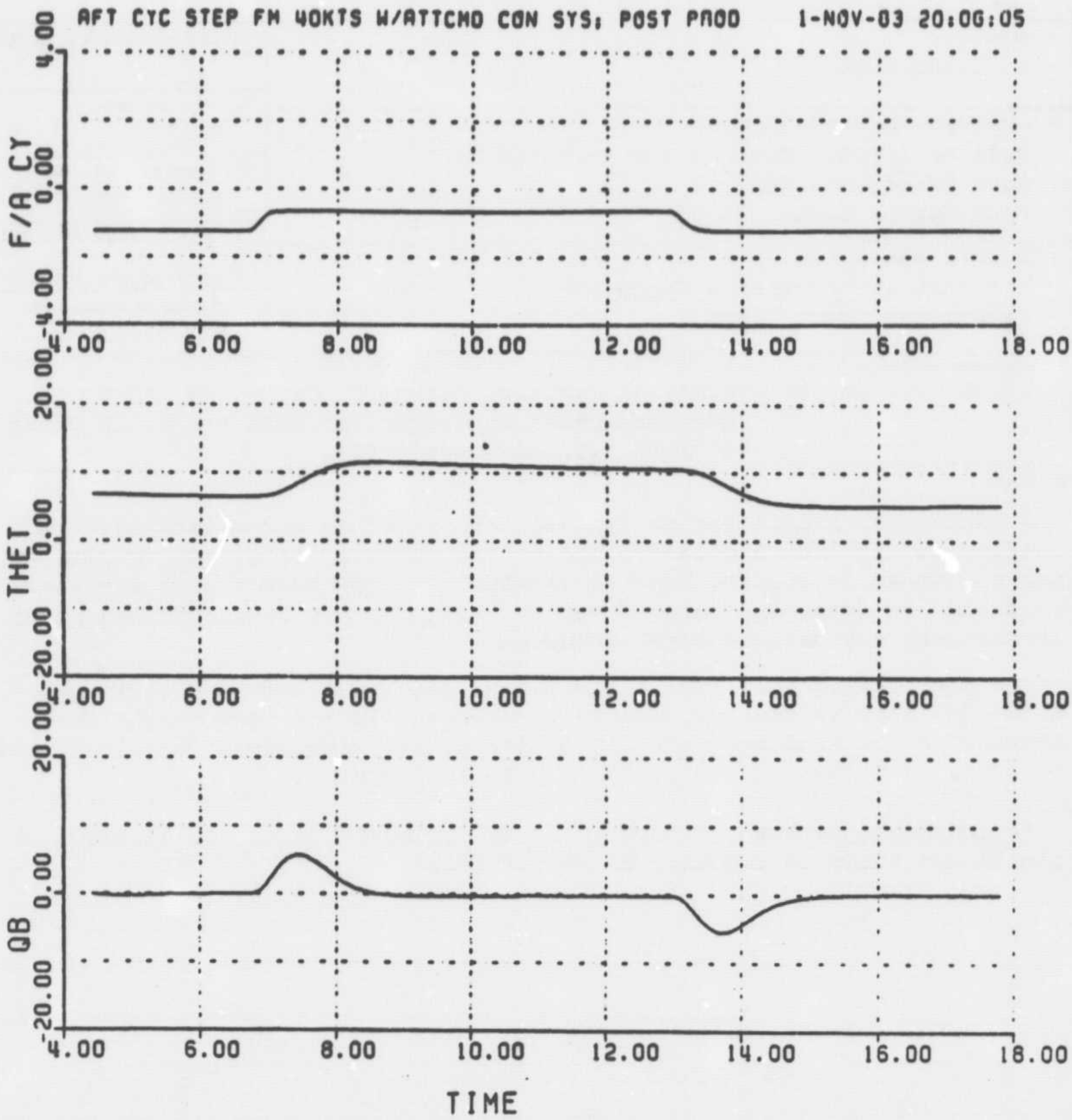

Figure B-7. Time history of attitude (THET) and rates (QB) response to step input in aft cyclic: postproduction ATTITUDE-COMMAND mode.

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15. Supplementary Notes

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16. Abstract

A simulation experiment to explore the use of an augmented pictorial display to approach and land a helicopter in zero visibility conditions was conducted in a fixed base simulator. A literature search was also conducted to determine related work. A display was developed and pilot in-the-loop evaluations were conducted.

The pictorial display was a simulated, high resolution radar image, augmented with various parameters to improve distance and motion cues. Approaches and landings were accomplished, but with higher workloads and less accuracy than necessary for a practical system.

Recommendations are provided for display improvements and a follow-on simulation study in a moving based simulator.

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